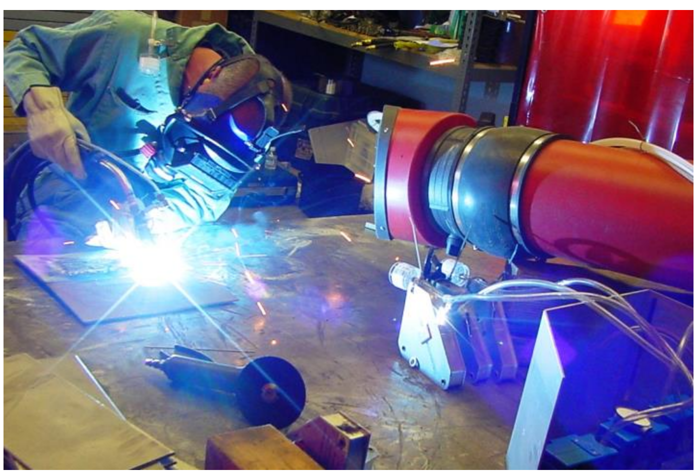
TECHNICAL REPORT
TR-NAVFAC-EXWC-EV-1508, VERSION 2
APRIL 2015

COST AND PERFORMANCE REPORT:

INTRODUCTION AND VALIDATION OF CHROMIUM-FREE CONSUMABLES FOR WELDING STAINLESS STEELS



Project Engineer: Kathleen Paulson, NAVFAC Engineering and Expeditionary Warfare Center
Contractor: Dr. Boian Alexandrov, The Ohio State University
Contractor: Dr. John Lippold, The Ohio State University

Participant: Tom Torres

This page intentionally left blank.

REPORT DOCUMENTATION PAGE

FORM APPROVED
OMB NO. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
09-04-2015

2. REPORT TYPE
Technical Report

3. DATES COVERED *(From – To)*
March 09-August 2013

4. TITLE AND SUBTITLE
Cost and Performance Report:
Introduction and Validation of Cr-free Consumables For Welding Stainless Steels, Version 2

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Kathleen Paulson
Boian Alexandrov
John Lippold

5d. PROJECT NUMBER
TR-NAVFAC-EXWC-EV-1508

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

NAVFAC Engineering and Expeditionary Warfare Center
1000 23rd Street, Port Hueneme, CA 93043

Ohio State University
281 West Lane Avenue, Columbus, OH 32611

8. PERFORMING ORGANIZATION REPORT NUMBER
TR-NAVFAC-EXWC-EV-1508, Version 2

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Environmental Security Technology Certification Program (ESTCP)
Phone (571) 372-6565 | Fax (571) 372-6386
4800 Mark Center Drive, Suite 17D08
Alexandria, VA 22350-3605

10. SPONSOR / MONITOR'S ACRONYM(S)
ESTCP

11. SPONSOR / MONITOR'S REPORT NUMBER(S)
ESTCP WP-4007

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Fusion welding of stainless steels results in the formation of Cr (VI) in the welding fume. The Cr (VI) is a carcinogen and is considered a significant health hazard for the welding personnel. In 2006, OSHA reduced the Permissible Exposure Limit (PEL) for Cr (VI) in welding fume from 52 to 5 micrograms per cubic meter 8-hour time weighted average. This regulatory change has imposed stringent requirements for reduction of Cr (VI) exposure during welding of stainless steel that necessitate considerable expense for ventilation systems and/or personal protective equipment.

The objective of this project was to demonstrate and validate two new chromium (Cr)-free welding consumables for application at the Department of Defense (DoD). These consumables have been developed as a replacement for the conventional consumables used to weld austenitic stainless steel and provide almost a 100-fold reduction of the carcinogenic hexavalent chromium in the welding fume of stainless steel. Welds of both Cr-free consumables met the performance objectives of 70,000 pounds per square inch tensile strength and successfully passed the bend test. During the Field Demonstration, some of the ENiCuRu welds contained lack of fusion defects and did not pass the X-ray test. Lack of fusion, lack of penetration, and undercut defects were found in welds made with the ERNiCuRu electrode.

15. SUBJECT TERMS
Welding, hexavalent chrome, ERNiCuRu, ENiCuRu

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Kathleen Paulson/Vern Novstrup
U	U	U	Click here	52	**19b. TELEPHONE NUMBER** *(include area code)* 805-982-4984/1276

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

DISCLAIMER:

This publication is intended to be informational and does not indicate endorsement of a particular product(s) or technology by the Department of Defense or NAVFAC EXWC, nor should the contents be construed as reflecting the official policy or position of any of those Agencies. Mention of specific product names, vendors or sources of information, trademarks, or manufacturers is for informational purposes only and does not constitute or imply an endorsement, recommendation, or favoring by the Department of Defense or NAVFAC EXWC. Although every attempt is made to provide reliable and accurate information, the authors of this publication do not warrant or otherwise represent in any way the accuracy, adequacy, efficiency, or applicability of any product or technology discussed or mentioned herein, including the suitability of any product or technology for a particular purpose.

COST AND PERFORMANCE REPORT

Introduction and Validation of Chromium-free Consumables for Welding Stainless Steels

ESTCP Project 09 E-WP-4007

Boian Alexandrov and John Lippold
Welding Engineering Program
The Ohio State University

Kathleen Paulson
NAVFAC Engineering and Expeditionary Warfare Center

Version 2

April
2015

Table of Contents

List of Figures

List of Tables

List of Acronyms

ABS	alpha/beta scalar
AED	Ammunition Equipment Division
Al	aluminum
α	alpha
ANSI	American National Standards Institute
APE	Ammunition Peculiar Equipment
AS	aerosol spectrometer
As	arsenic
ASTM	American Society for Testing and Materials
AWS	American Welding Society
β	beta
Cd	cadmium
CFM	cubic feet per minute
Co	cobalt
Cr	chromium
Cr (VI)	hexavalent chromium
Cu	copper
DAC	derived air concentration
DCP	Direct Coupled Plasma
DoD	Department of Defense
ECM	Environmental Cost Management
E308L-16	Shielded metal arc welding electrode alloyed with chromium, nickel, and with low carbon content
El	elongation
ELPI	electric low pressure impactor
ENiCuRu	Shielded metal arc welding electrode alloyed with nickel, copper, and ruthenium
ER308LSi	Solid wire gas-metal arc electrode alloyed with chromium, nickel, silicon, and with low carbon content
ERNiCuRu	Solid wire gas-metal arc welding electrode alloyed with nickel, copper, and ruthenium
ESTCP	Environmental Security Technology Certification Program
Fe	iron
FGR	fume generation rate
γ	gamma
GECRM	gamma exposure and count rate meter
GMAW	gas metal arc welding

GTAW	gas tungsten arc welding
HAP	Hazardous Air Pollutants
ICP	inductively coupled plasma
IH	industrial hygiene
ISO	International Organization for Standardization
K	potassium
K_2CrO_4	potassium chromate
ksi	kilopounds per square inch
lb	pound
lbs	pounds
MCE	mixed cellulose ester
μg	micrograms
$\mu g/m^3$	micrograms per cubic meter
mg/m^3	milligrams per cubic meters
Mg	magnesium
Mn	manganese
Mo	molybdenum
Na	sodium
NaF	sodium fluoride
NDE	Nondestructive Evaluation
Ni	nickel
NIOSH	National Institute for Occupational Safety and Health
NSWCCD	Naval Surface Warfare Center Carderock Division
O	oxygen
OSHA	Occupational Safety and Health Administration
Pb	lead
Pd	palladium
PEL	Permissible Exposure Limit
PI	Principle Investigator
PPE	personal protective equipment
PVC	polyvinyl chloride
RD	radiation detector
Ru	Ruthenium
SEM	scanning electron microscope
SERDP	Strategic Environmental Research and Development Program
Si	silicone
SMAW	shielded metal arc welding

Sr	strontium
TEAD	Tooele Army Depot
Ti	titanium
TWA	time-weighted average
UHR	ultra-high resolution
UTS	ultimate tensile strength
V	vanadium
wt %	weight percent
XEDS	X-ray energy dispersive spectroscopy
XRD	X-ray diffraction
XRF	X-ray fluorescence
YS	yield strength
Zn	zinc

Executive Summary

Objective of the Demonstration

The objective of this project was to demonstrate and validate two new chromium (Cr)-free welding consumables for application at the Department of Defense (DoD). These consumables have been developed as a replacement for the conventional consumables used to weld austenitic stainless steel and provide almost a 100-fold reduction of the carcinogenic hexavalent chromium (Cr(VI)) in the welding fume of stainless steel.

This project was developed in two stages: laboratory demonstration and field demonstration. The objective of the laboratory demonstration was further optimization of the two Cr-free welding consumables aiming to ensure full compliance with the relevant American Welding Society (AWS), American Society for Testing and Materials (ASTM), International Organization for Standardization (ISO), and Occupational Safety and Health Administration (OSHA) codes and regulations.

The objective of the field demonstration was to conduct on-site demonstration and validation of the optimized Cr-free welding consumables during typical welding operations in fabrication of stainless steel. The performance objectives included: 1) 90% reduction in exposure to Cr(VI) and in hazardous air emissions, 2) production of welds with mechanical properties that meet relevant AWS specifications and are free of defects, and 3) demonstration of acceptable welding operability. These performance objectives were successfully met during the field demonstration and validation.

Technology Description

Fusion welding of stainless steels results in the formation of Cr(VI) in the welding fume. The Cr(VI) is a carcinogen and is considered a significant health hazard for the welding personnel. In 2006, OSHA reduced the permissible exposure limit (PEL) for Cr(VI) in welding fume from 52 to 5 micrograms per cubic meter 8-hour time weighted average (TWA). This regulatory change has imposed stringent requirements for reduction of Cr(VI) exposure during welding of stainless steel that necessitate considerable expense for ventilation systems and/or personal protective equipment (PPE).

New Cr-free shielded metal arc welding (SMAW) and gas metal arc welding (GMAW) consumables have been developed as a replacement for the conventional Types 308 and 316 stainless steel welding consumables. These new Cr-free consumables provide almost a 100-fold reduction of Cr(VI) in the welding fume and produce welds with comparable corrosion resistance and mechanical properties relative to the conventional stainless steel consumables. In some conditions relevant to DoD interests, such as cramped ship interiors, it is extremely difficult or/and cost prohibitive to ventilate effectively or to perform welding operations using PPE. For such conditions, the newly developed Cr-free welding consumables provide a feasible alternative for meeting the OSHA PEL for Cr(VI) in the welding fume.

Demonstration Results

The main objective of this demonstration was successfully achieved: 90% reduction in Cr(VI) and hazardous air emission during welding with the newly developed Cr-free shielded metal arc welding (SMAW) ENiCuRu and gas metal arc welding (GMAW) ERNiCuRu electrodes. The

ENiCuRu electrode provided reduction in Cr(VI) exposure of more than 92% compared to the OSHA PEL and more than 94% compared to the conventional E308L-16 electrode.

The ERNiCuRu electrode provided reduction in Cr(VI) exposure of more than 71% compared to the conventional E308L-16 electrode. The fume content of copper (Cu) and nickel (Ni) was up to two orders of magnitude higher than in the conventional ER308LSi and single measurements exceeded the OSHA PELs. Such behavior is expected since ERNiCuRu is a Ni-based welding consumable with a high alloy content of Cu. A possible solution for reduction of these Ni and Cu emissions would be using this electrode with a low heat input GMAW process such as cold metal transfer.

The emission of metallic elements (Cu, iron, manganese, arsenic, cadmium, cobalt, molybdenum, lead, strontium, vanadium, and zinc) in the fume of both Cr-free consumables was between two and four orders of magnitude lower than the corresponding OSHA PELs. The emission of ruthenium (Ru) in the fume of these electrodes was extremely low (0.0003 to 0.0044 milligrams per cubic meters), and in most measurements below the limit of quantitation. There is currently no OSHA PEL for Ru. A point of concern related to the presence of Ru in the Cr-free electrodes was possible exposure to radiation generated by Ru isotopes. The field screening for alpha, beta, and gamma radiation showed peak counts that were on the order of the background radiation. The exposure to radiation of the welding personnel was two orders of magnitude lower than the derived air concentration for Ru isotopes of ^{106}Ru 5×10^{-9} μCi/ml).

Welds of both Cr-free consumables met the performance objectives of 70,000 pounds per square inch tensile strength and successfully passed the bend test. During the laboratory demonstration, the ENiCuRu and ERNiCuRu electrodes produced high quality welds free of defects. During the field demonstration, some of the ENiCuRu welds lacked fusion defects and did not pass the X-ray test. Lack of fusion, lack of penetration, and undercut defects were found in welds made with the ERNiCuRu electrode. Similar defects were found in welds of conventional E308L-16 and ER308LSi electrodes. Particular defect-free welds of both the ENiCuRu and ERNiCuRu consumables met the performance objective of 30% minimum elongation (El). Defect containing welds of both the Cr-free consumables and the conventional reference electrodes had El less than 30%. The weld quality achieved during the laboratory and field demonstrations reflected welders' experience with Ni-based welding consumables. Both Cr-free welding consumables demonstrated good welding operability and arc stability, comparable to conventional Ni-based welding consumables.

Implementation Issues

One issue related to the implementation of the Cr-free ENiCuRu and ERNiCuRu welding consumables may be the absence of an OSHA PEL for Ru in welding fume. In fact, no published occupational exposure limits for Ru in any of the literature was found. This issue can be addressed by conducting related studies at particular National Institute for Occupational Safety and Health (NIOSH) or DoD laboratories. Another implementation issue is the need for additional training of welders who have no experience working with Ni-based welding consumables.

1.0 Introduction

1.1 Background

Stainless steels are usually selected as a material of construction for their corrosion resistance. When they are fabricated into structures, stainless steel components are often joined by welding. To ensure that the welds exhibit sufficient corrosion resistance, filler metals matching or exceeding the chromium (Cr) content of the base metal must be used. The Cr content of Types 304 and 308 stainless steels, the most commonly used stainless steel based metal and the filler metal used to weld it, respectively, is 18 to 20 weight percent (wt %). Fusion welding of these steels results in the formation of carcinogenic hexavalent chromium (Cr(VI)) in the fumes. This is a significant health hazard for the welders and necessitates considerable expense for ventilation systems, and potential longer term expense dealing with litigation. In some conditions relevant to Department of Defense (DoD) interests, such as cramped ship interiors, it is extremely difficult to ventilate effectively. DoD facilities are required to estimate the residual risk to public health and, in certain states, must report the findings to the public when cancer risk exceeds a threshold of one in one million. When the threshold is exceeded, the facility is also expected to initiate measures to reduce the fugitive emissions.

New Cr-free shielded metal arc welding (SMAW) and gas metal arc welding (GMAW) consumables have been developed as a replacement for conventional stainless steel consumables such as Types 308, 309, and 316 for welding austenitic stainless steel based metal. These new consumables have comparable corrosion resistance and mechanical properties relative to the consumables they are designed to replace. The measured Cr(VI) in the fume of the SMAW electrode when welding Type 304 stainless steel is virtually zero (0.02 wt %) and represents a 100-fold reduction in Cr(VI) relative to a conventional Type 308 consumable.

Using the newly developed Cr-free welding consumables, DoD can reduce the fugitive emissions of carcinogenic Cr(VI) generated during welding operations. The Cr-free consumables can be used to replace conventional stainless steel welding consumables during specific welding operations to meet the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL) for Cr(VI), especially when using ventilation and/or personal protective equipment (PPE) is impossible and/or cost prohibitive.

1.2 Objective of the Demonstration

Under the laboratory demonstration stage of this project, further optimization of the Cr-free SMAW and GMAW consumables was conducted to improve their welding operability characteristics. The objective of the laboratory demonstration was to establish performance objectives and acceptance criteria, and apply these during laboratory testing of the optimized Cr-free ENiCuRu and ERNiCuRu consumables in order to ensure full compliance with the relevant American Welding Society (AWS), American Society for Testing and Materials (ASTM), International Organization for Standardization (ISO), and OSHA codes and regulations.

The objective of the field demonstration was to conduct on-site demonstration and validation of the optimized heats of the Cr-free SMAW ENiCuRu and GMAW ERNiCuRu consumables during typical welding operations in fabrication of stainless steel. This demonstration was performed at the Tooele Army Depot (TEAD), Ammunition Equipment Division (AED), Tooele, UT.

The performance objectives for the field demonstration of the Cr-free SMAW and GMAW consumables included:

- Meeting the OSHA PEL of 5 micrograms per cubic meters ($\mu g/m^3$) time-weighted average (TWA) for Cr(VI);
- Providing comparable welding operability and welder's satisfaction to the conventional E308L and ER308L welding consumables; and
- Weld mechanical properties exceeding the minimum requirements for Type 304L stainless steel and comparable to welds of conventional E308L and ER308L consumables.

All of these performance objectives were successfully met during the field demonstration and validation. The targeted hazardous materials, the current processes, applications, and specifications, and the affected programs and potential applications of the new Cr-free welding consumables are listed in Table 1-1.

Table 1-1. Target Hazardous Material Summary

Target Hazardous Material	Current Process	Applications	Current Specifications	Affected Programs	Candidate Parts and Substrates
E308L, E309, E316 ER308, ER309, ER316	SMAW GMAW GTAW	Welding of type 304, 309 and 316 stainless steels	AWS A5.4 AWS A5.9	Repair welding of stainless steel in confined spaces	Navy ships and DoD facilities where effective welding fume ventilation is impossible or impractical

GTAW – gas tungsten arc welding

1.3 Regulatory Drivers

The main regulatory driver for the development of this project is the recent reduction in the PEL for Cr(VI) in welding fume from 52 to 5 $\mu g/m^3$ 8-hour-TWA introduced by OSHA [1, 2].

2.0 Demonstration Technology

2.1 Technology Description

The main objectives in the Cr-free consumable development was to achieve elimination of the carcinogenic Cr(VI) in the welding fume during stainless steel welding and to provide a compatible replacement of the standard stainless steel welding consumables in terms of weld corrosion resistance, mechanical properties, and consumable welding operability. To achieve these objectives the following design criteria were imposed:

- The breakdown and repassivation potentials of the weld metal should be higher than the corrosion potential of the stainless steel substrate to prevent localized attack of the weld metal.
- If possible, the corrosion potential of the weld metal should be slightly higher than that of the stainless steel substrate so that the weld metal is cathodically protected.
- The strength and ductility of the welds must meet or exceed minimum requirements for the base metals they join.
- Weldability, including susceptibility to various forms of cracking during welding, should be within the range of comparable consumables.
- The operating characteristics of the consumable should be such that it can be readily used in applications requiring manual, semi-automatic, and fully automated welding processes.

Two welding Cr-free consumables have been developed that meet the design criteria listed above: ENiCuRu for SMAW and ERNiCuRu for GMAW. The final target weld metal composition that meets the design requirements for strength and corrosion resistance is nominally nickel (Ni)-7.5 copper (Cu)-1 ruthenium (Ru)-0.5 titanium (Ti). This is the composition of the ERNiCuRu electrode for GMAW. In the coated ENiCuRu electrode for SMAW, this composition is achieved by over-alloying the core wire with Ti.

The developed Cr-free welding consumables were subjected to extensive corrosion, mechanical, and weldability testing, and fume characterization in the frame work of the Strategic Environmental Research and Development Program (SERDP) Project PP-1415 [3]. The test results have confirmed that the main design criteria were successfully met. The content of Cr(VI) in the welding fume of Cr-free electrode was more than two orders of magnitude lower than in the conventional E308-16 electrode. Based on comparison in the fume generation rates, the Cr(VI) generation rate in the Cr-free consumable was estimated to be approximately 60 times lower than in the E308-16 electrode for similar welding conditions. The mechanical properties of the Cr-free consumable exceeded the minimum strength, elongation (El), and reduction in area of Type 304L stainless steel and E308L weld metal, as shown in Table 2.1.

Table 2-1. Mechanical Properties of Ni-Cu, Ni-Cu-Pd, and Ni-Cu-Ru Weld Metals

Weld Metal	Base Metal	Failure Location	Tensile Strength, MPa	El, %	Reduction in Area, %
Ni-Cu-Ru	304L	Weld Metal	540	52.0	54.0
304L Minimum Values			480	40	50
E308L-16 Typical Values			517	35	-

Pd – palladium

2.2 Advantages and Limitations of the Technology

The new Cr-free welding consumable produces welds with mechanical properties that fulfill the requirements for Type 304 stainless steel and are comparable to the mechanical properties of the standard type E308 electrodes for stainless steel welding. This new consumable has welding operability, weldability, and fume generation rates (FGRs) that are similar to the standard stainless steel electrodes.

The main advantage of the new Cr-free welding consumable over the conventional type E308 welding electrodes is that it nearly completely eliminates the carcinogenic Cr(VI) in the welding fume generated during welding of austenitic stainless steel. Use of this electrode will allow the new OSHA PEL for Cr(VI) to be routinely met in shop and field welding applications. There are no other available stainless steel consumables for welding the 300-series stainless steels that will meet the OSHA PEL.

The disadvantage of the new Cr-free welding consumable is its high price. The cost analysis of the older version of this consumable that was alloyed with 1 wt % palladium (Pd) had predicted an increase in the welding cost at Navy shipyards between 75 and 200%. This cost analysis was based on the price of Pd at $4,500/lb. In the last formulation of this consumable that has been optimized in the current project, the Pd was substituted with Ru. Due to the lower price of Ru, this substitution will significantly reduce the costs of welding operations with the new consumable. A detailed cost analysis for the application of the new Cr-free consumable at DoD facilities is presented in Section 7.0 of this report.

A possible limitation to the implementation of the Cr-free ENiCuRu and ERNiCuRu welding consumables could be the need for additional training of welders who have no experience working with Ni-based welding consumables.

3.0 **Performance Objectives**

The performance objectives of the field demonstration have been selected to provide reliable validation of the Cr-free SMAW and GMAW consumables during stainless steel welding that most closely replicate the welding operations in fabrication of stainless steel at DoD facilities. Parallel testing of the new technology (Cr-free consumables) versus the conventional technology (stainless steel consumables) was performed during the field demonstration to ensure that all performance objectives were met. The performance objectives are described in Table 3-1.

The first performance objective addresses the weldability evaluation and the mechanical properties of stainless steel welds produced with the Cr-free consumables. This objective ensures that the innovative consumables have at least equivalent performance to the existing welding technology. The field test results show that this performance objective has been met and the demonstrated Cr-free consumables have equivalent performance to the existing technology.

The second and third performance objectives address the criteria verifying that hazardous air emissions and occupational exposures will be reduced with the application of the innovative Cr-free welding consumables. The success criterion is a Cr(VI) reduction of greater than 90% for the Cr-free consumables versus the conventional technology. Test methods used for the area sampling are typical industrial hygiene engineering sampling methodologies. The field test results show that this performance objective has been met and the demonstrated Cr-free consumables provide greater than 90% Cr(VI) reduction compared to the existing technology.

There is currently no published occupational exposure limit for Ru and the field test results cannot be compared to established guidelines or standards. It is expect that the Navy Toxicology Detachment will recommend limits based on similar materials and these findings.

The fourth performance objective addresses the ease of use of the Cr-free welding consumables and ensures that these consumables have similar welding operability as the conventional stainless steel electrodes. The welders reported that the welding process for Cr-free consumables would require training and the operability of the process was found to be acceptable.

Table 3-1. Performance Objectives

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Weldability, Welding Operability, and Mechanical Properties	Nondestructive testing - e.g. radiography, ultrasonic, magnetic particles, liquid penetrate, eddy current Chemical – composition and corrosion Metallography – LOM, etc. Mechanical – e.g. hardness, tensile strength, yield strength, and ductility Joints – bend, tensile strength, fillet weld, fracture toughness	Equivalent to existing welding performance tests for the specific activity Comply with: • AWS D1.6/D1.6M:2007 Structural Welding Code [4] • AWS 5.11 [5]: Mechanical – Ultimate Tensile Strength 70 kilopounds per square inch (ksi), 30% El, Weldability - Acceptable defect level	Objective met Objective met Objective met Objective met
Reduction of Hazardous Air Emissions	Hazardous air pollutants (HAPs) emissions evaluations including heavy metals: Cr(VI), total Cr, Ni, Cu, manganese (Mn), Ru, Ti, etc.	90% reduction of HAP metals from current process vs. for Cr-free consumable process, Ru exposures below TBD level recommended by Navy Toxicology Detachment	Objective met Objective met
Reduction in Occupational Exposure Limits	Navy Marine Corps Public Health Center Field Operations Manual for Sampling Procedures. National Institute for Occupational Safety and Health 7303 Metal Elements by inductively coupled plasma (Nitric/Perchloric Acid Ashing) - total Cr, Mn, Ni, Cu, Ru, Ti, etc. OSHA 215 – Cr (VI)	Cr free Consumables >90% reduction in Cr(VI) OSHA exposures. Other metals below the OSHA PEL action level (where available). Provide emissions data for Ru since there is no PEL.	Objective met 0.0002 to 0.0044 mg/m^3
Qualitative Performance Objectives			
Ease of use (welder's appeal)	Feedback from field technician on stability of technology. Tracking time to weld (inches per minute)	Welder Acceptance. Reduction or equivalent time to weld.	Objective met

mg/m^3 – milligrams per cubic meters

4.0 Site/Platform Description

4.1 Test Platforms/Facilities

The TEAD, AED was selected as the test site for the field demonstration, which took place in August 2011.

The TEAD, a government-owned/government-operated facility, offers both engineering and ammunition expertise through a wide variety of applications, including design and manufacturing of Ammunition Peculiar Equipment (APE) used in maintenance and demilitarization for DoD. Tooele's products and services are available to other government agencies, contractors, and foreign allies. TEAD is ISO 9001:2000 certified. The 23,732-acre site is located in northeastern Tooele County, UT, about 35 miles southwest of Salt Lake City.

TEAD is the Center of Industrial and Technical Excellence for depot-level activities in support of APE. Since 1955, TEAD has been designing, prototyping, fielding, and providing maintenance/training for the ammunition equipment installed at installations in the continental United States and outside the continental United States. TEAD plays a role in the engineering and manufacturing support of chemical demilitarization equipment. The special metal and welding requirements were a challenge Ammunition Equipment and Manufacturing Directorate was able to meet as its welders fabricate conventional furnaces/chemical equipment from stainless steel material with special welding requirements and also in fabricating explosive barricades and ammunition storage containers.

4.2 Present Operations

TEAD uses welding operations for joining of Type 304 stainless steel in the fabrication of APE. The welding operations in Type 304 stainless steel are performed using SMAW, GMAW, and GTAW processes with conventional welding consumables E308L (SMAW) and ER308L (GMAW and GTAW). TEAD AED designs and builds unique equipment specific to a particular ammunition maintenance, surveillance, or demolition need. Some years, TEAD may use up to 500 pounds (lbs) of consumables for 304 base metal; other years the usage may be minimal.

The two Cr-free welding consumables that are demonstrated in this project are intended to replace the conventional stainless steel welding electrodes that generate a significant amount of Cr(VI) in welding fume. Type 304 steel plates with thicknesses of 0.25 in. and 0.5 in. were welded with the Cr-free SMAW and GMAW consumables to demonstrate and validate their application as a replacement of the conventional stainless consumables in typical operational conditions at TEAD.

4.3 Site-Related Permits and Regulations

No site permits are required to conduct these tests. The operations were direct duplicates of the current work practices except for consumable materials and the shield gas. All visiting personnel were required to abide by the installation contractor clauses and were provided with those clauses.

5.0 **Test Design**

5.1 Laboratory Testing

The test plan of the laboratory demonstration was designed to ensure that the optimized consumables meet the performance objectives and the corresponding acceptance criteria specified in Table 3-1. Performance Objectives. The tests used in the laboratory demonstration are described below.

5.1.1 Mechanical Testing

The mechanical testing included tensile and bend tests of welds in 304L stainless steel produced with the Cr-free ENiCuRu in ERNiCuRu consumables. The test weld assemblies corresponded to American National Standards Institute (ANSI)/AWS B4.0-98, ANSI/AWS A5.11-97, and ANSI/AWS A5.4-92 [5-7].

One ENiCuRu all weld metal tensile test sample with 0.5 in. diameter and 2 in. gauge length, and three ERNiCuRu cross weld tensile test samples with 0.25 in. thickness were prepared and tested. The samples' geometry corresponded to ANSI/AWS B4.0-98, ANSI/AWS A5.11-97, and ANSI/AWS A5.4-92. The tensile testing was performed in accordance with ASTM E8 [8].

Three side bent samples were machined out of each the ENiCuRu and the ERNiCuRu weld test assemblies. The test weld assemblies and sample geometries corresponded to ANSI/AWS B4.0-98. The bend testing was performed in accordance with ANSI/AWS B4.0-98 and ASTM E190 [6]. The procedures used in production of all weld test assemblies are described in the Final Report [9].

5.1.2 Radiography

The 0.75 inch ENiCuRu weld test assembly and the 0.25 inch thick ERNiCuRu test assembly were subjected to radiographic testing. The testing was performed in accordance with the radiography procedures specified in ANSI/AWS B4.0-98 and ASTM E142 [6, 10].

5.1.3 Welding Operability

The welding operability of the ENiCuRu electrode was qualitatively evaluated and compared to conventional Ni-based welding consumables by two highly experienced welders at Energy Solution Group. The welding operability was assessed on a 0.75 inch thick test butt weld assembly and a series of fillet welds in 0.25 inch thick type 304L stainless steel in flat, vertical down, and overhead positions. The welding procedures, evaluation criteria, and rating schedule are given in the Final Report [9]. Additional evaluation of arc stability was performed using simultaneous recording of the arc current and voltage of the ENiCuRu electrode and a conventional Ni-based electrode during fully mechanized SMAW. Semiquantitative evaluation of arc stability was performed by comparing three-dimensional plots of current - voltage - time and current - voltage - % occurrence for the two electrodes.

5.1.4 Macro- and Micro-structure Examination

Weld test assemblies used for mechanical testing and welding operability evaluations were prepared for metallurgical evaluation using standard metallography practices. All samples were electrolytically etched in 10% oxalic acid at 6V 1A current for 2 minutes. The characterization was performed using optical microscopy at magnification of 5x to 1000x.

5.1.5 Composition Analyses

Chemical analyses of all weld metal deposits from the ENiCuRu consumable and of the ERNiCuRu filler wire were performed using standardized analysis techniques as follows:

- Direct Coupled Plasma (DCP): ASTM E1097-07/CTP 3005/DCP [11]
- X-ray fluorescence (XRF): ASTM E1621-09/CTP 3093/XRF [12]
- Oxygen and Nitrogen: ASTM E1019-08/CTP 3097/IG [13]
- Carbon and Sulfur: ASTM E1019-08/CO [13].

5.1.6 Fume Analyses

A total of three welding consumables were tested:

- The optimized Cr-free SMAW ENiCuRu electrode of 1/8 inch diameter;
- The Cr-free GMAW ERNiCuRu filler wire of 0.045 inch diameter; and
- A conventional GMAW ER308LSi filler wire of 0.045 inch diameter, to be used as a baseline for comparison to the Cr-free ERNiCuRu filler wire.

Previous results from a conventional SMAW E308L-16 electrode were used as a baseline for comparison to the Cr-free ENiCuRu electrode. Welds of the three tested consumables were deposited on a 3/8 inch thickness plate of type 304L stainless steel.

The welding fume for determination of FGR and the Cr(VI) content in the fume, and for X-ray diffraction (XRD) analyses was collected using a modified AWS F1.2:2006 type fume hood [14]. The fume generated by the tested electrodes was drawn in with a 40 cubic feet per minute (cfm) flow rate and collected onto 0.3 micrometer Staplex glass fiber filters until the flow rate dropped to approximately 10 to 15 cfm. The FGR was calculated using formula (1):

$$\text{FGR} = (W_f - W_i)/t, \qquad (1)$$

where $\boldsymbol{W_f}$ is the final weight of the filter, $\boldsymbol{W_i}$ is the initial weight of the filter, and $\boldsymbol{t}$ is the collection time.

The Cr(VI) content in the fume of ENiCuRu electrode was analyzed using the colorimetric method with diphenyl carbazide in accordance with ISO 3613:2000. Not enough fumes were collected during the FGR testing of the ERNiCuRu filler wire to analyze the Cr(VI) content in the fume of this electrode. The Ru content in the welding fume was analyzed using inductively coupled plasma (ICP) spectrometry. XRD analyses of the welding fume were performed using a Scintag XDS-2000 diffractometer equipped with a Cu x-ray tube.

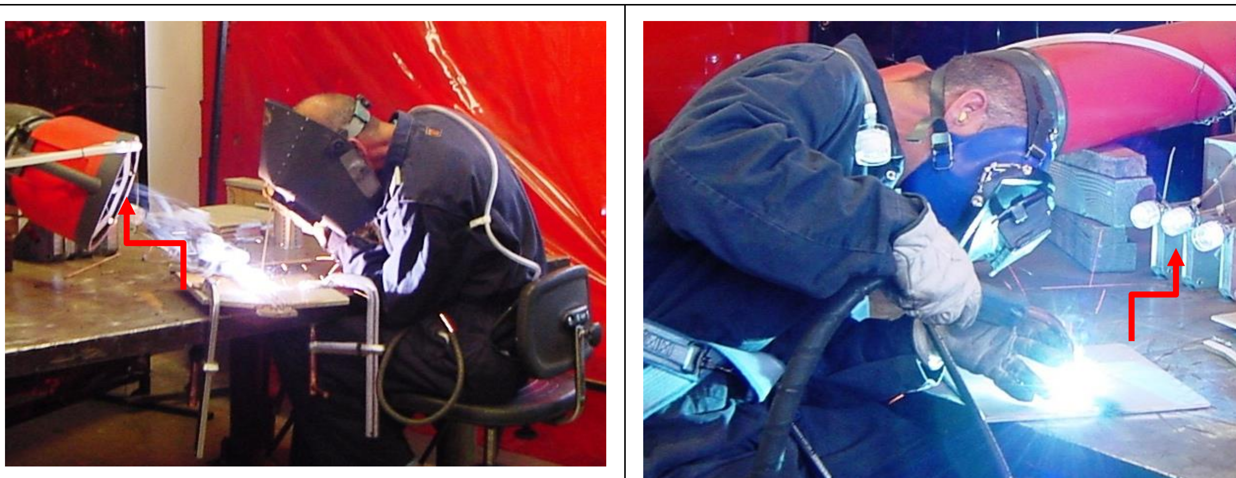
The mass and size distribution of fume particles in the welding fume was studied using a Dekati Ltd. 10 liter per minute electrical low pressure impactor (ELPI). The morphology, size, distribution, and composition of the particles in the welding fume of Cr-free and conventional welding consumables were characterized using scanning electron microscope (SEM) with ultra-high resolution (UHR) and X-ray energy dispersive spectroscopy (XEDS). The welding parameters used in the fume generation tests and all fume analysis procedures are provided in the Final Report [9].

5.2 Field Testing

The field demonstration was conducted at TEAD. The test plan for the field demonstration was designed to provide reliable validation of the Cr-free SMAW and GMAW consumables during stainless steel welding that most closely replicates the welding operations in fabrication of stainless steel at DoD facilities.

5.2.1 Production of Weld Test Assemblies

The weld test assemblies were produced by a DoD welder during the field demonstration at TEAD. Six weld test assemblies were produced with each of the tested Cr-free ENiCuRu and ERNiCuRu consumables and baseline E308L-16 and ER308LSi consumables. Figure 5-1 shows the welding processes involved in the production of each type of weld test assembly. The detailed welding procedures are provided in the Final Report [9].



a) b)

Figure 5-1. Field Demonstration Welding Processes

a) SMAW with Cr-free ENiCuRu and baseline E308L-16 electrodes, b) GMAW with Cr-free ERNiCuRu and baseline ER308LSi filler wires. Red arrows point to aerosol spectrometer and ELPI sampling tubes.

5.2.2 Field Welding Fume Collection and Occupational Safety Hygiene and Environmental Testing

The welding fume collection and occupational safety hygiene and environmental testing during the field demonstration at TEAD were conducted by Environmental Cost Management (ECM), Inc., Mesa, AZ. The testing procedures presented below were developed by ECM.

The field welding occurred over 12 days during 3 weeks in August 2011. The equipment used for air monitoring during these field tests included:

- Six industrial hygiene (IH) air pumps, with calibrated airflow rates
- GRIMM Technologies, Inc. Model Number 1.109 aerosol spectrometer (AS) for collection of airborne particles
- Dekati Ltd. ELPI – airborne particle collection and separation by size
- Ludlum Measurements, Inc. Model Number 44-9 radiation detector (RD) for beta (β) and gamma (γ) detection for field screening of personnel and work areas
- Ludlum Measurements, Inc. Model Number 2929 alpha/beta scalar (ABS) for measuring alpha (α), β, and γ radiation of spent filtration media,
- CES- Landtec GEM 2000 for combustible gas, oxygen and carbon dioxide monitoring.

5.2.3 Field Welding Air Monitoring Setup

The area used for welding was a room that had several doors, a double door on an inside wall, a hallway door, a large roll-up door on an exterior wall, and two windows. The exterior doors and windows were closed during testing. The interior doors were sealed off using duct tape and plastic sheeting. All doors were closed, openings taped shut and no one was allowed to go in or out of the room during welding.

The AS and ELPI were set up in a room adjacent to the welding area (Figure 5-2). The air sampling tubes attached to each of the machines were attached to the Lincoln Collector duct located above the welding work table (Figures 5-1 and 5-3).

a)

b)

Figure 5-2. AS and ELPI Apparatus
a) AS, b) ELPI apparatus

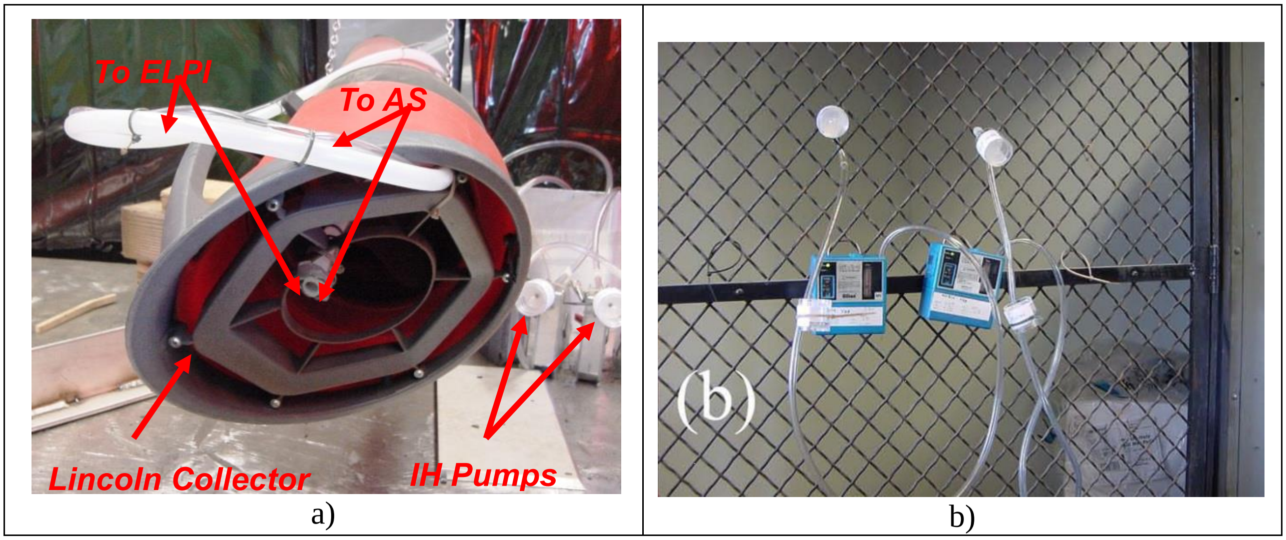


Figure 5-3. Lincoln Collector and Near Fields Sampling
a) the Lincoln Collector and b) near fields sampling during field welding

The AS used 47-mm polyvinyl chloride (PVC) filters, which were analyzed for metals and Ru by the National Institute for Occupational Safety and Health (NIOSH) 7303, and for Cr(VI) by OSHA ID 215. The ELPI instrument was provided by the Ohio State University and required a set of 13 PVC filters during each run. Filters were analyzed for metals and Ru by NIOSH 7303 and for Cr(VI) by OSHA ID 215.

Four to six IH pumps were positioned in the welding room, fitted with filter cartridges on the intake tubing. The cartridges had PVC or mixed cellulose ester (MCE) filters, depending on the analyte being tested. For each test, there was a set of pumps positioned on the work table (near field, Figures 5-1b and 5-3a) and another set positioned approximately 10 feet away from the work table (far field, Figure 5-3b). The pumps positioning, filters, and analytical test methods are listed below:

- Pump 1 – NIOSH 7303 – 37 mm MCE filter, all metals near field
- Pump 2 – NIOSH 7303 - 37 mm MCE filter, all metals far field
- Pump 3 – OSHA ID-215 revision 2 – 37 mm PVC filter, (Cr(VI)) near field
- Pump 4 – OSHA ID-215 revision 2 – 37 mm PVC filter, Cr(VI) far field
- Pump 5 – NIOSH 7501 – 37 mm PVC filter, Amorphous Silica – near field
- Pump 6 – NIOSH 7501 – 37 mm PVC filter, Amorphous Silica – far field
- NIOSH 7600 Ru – far field (Lab indicates Pump 2 – 7303 diluents can be used)

The testing and calibration procedures for the AS, ELPI, and the IH pumps are described in full detail in the Final Report [9].

Health and Safety Monitoring

Health and safety issues and procedures for monitoring test participants (welder, observer) and ECM personnel were addressed as outlined in the document "Safety Program Plan for Hazardous

Air Pollutants Emissions Sampling Environmental Security Technology Certification Program (ESTCP) Innovative Welding Technology" [3]. The welding room was sealed during all welding tests as described above. The welding method being demonstrated by the Ohio State University was a Cr-free method not involving possible exposure to Ru. Beta radiation is primarily emitted by Ru isotopes; however, γ radiation may be detected from some unstable isotopes such as ^{97}Ru and ^{103}Ru.

The monitoring was performed in two ways. Field screening was done using the RD in conjunction with the Ludlum Measurements, Inc. Model Number 3-97 γ exposure and count rate meter (GECRM). The ABS was used to quantitatively measure the amount of radiation each person received daily while in the room during welding. The welding table, welding rod, and the welding plates were monitored daily. People working in the welding room were typically monitored in the morning, before leaving for a lunch break, before entering the room after lunch and then at the end of the day. The results indicated mostly β radiation, and the derived air concentration (DAC) never exceeded the project action levels.

QA/QC

The following quality control samples were collected during the course of field testing:

- One blank filter from each lot of filters: untouched and sent directly to the lab for analysis.
- Field blanks - filters with seals broken and packaged similar to other samples. No air was drawn through these filters but they were handled similarly to other samples. One field blank per day was prepared from the following filters: OSHA ID-215 revision 2 Cr(VI); NIOSH 7303 (All Metals); NIOSH 7600 (Ru).

In addition, a sample was run on the ELPI for 15 minutes to measure the ambient air within the instrument room to see if the particles from the welding area were coming into the neighboring space. The filters were analyzed for metals, Ru and Cr(VI).

5.2.4 Analysis of Welding Fume Collected during Field Demonstration

The analyses of all fume samples collected during the field testing was performed at the Navy and Marine Corps Public Health Center Comprehensive Industrial Hygiene Laboratory in San Diego, CA. The following analysis procedures were used: 1) for Cr(VI): OSHA 215 and NIOSH 7600 using ion chromatography; 2) for Ru and other metals: NIOSH 7300 using ICP with an Aglient ICP-MS 7700 instrument.

5.2.5 Mechanical and Quality Testing of Welds Produced during Field Demonstration

Weld test assemblies produced with the Cr-free consumables and with the baseline consumables were subjected to mechanical testing, metallographic characterization, chemical analysis, and radiographic examination at the Naval Surface Warfare Center Carderock Division (NSWCCD). The test plan is shown in Table 5-1.

The tensile testing was conducted in accordance with ASTM E8 [8]. The gas metal arc welds were subjected to transverse tensile testing in accordance with ANSI/AWS B 4.0 [6] and ANSI/AWS A5.4-9 [7]. All weld metal tensile testing was performed in accordance with ANSI/AWS B 4.0 [6] and ANSI/AWS A5.11-97 [5].

Standard metallographic techniques were used for sample extraction, mounting, polishing and etching in accordance with ASTM E 407 [15]. The chemical analyses were conducted in accordance with ASTM E1019 [13] for carbon and sulfur, ASTM E1019 [13] for nitrogen, and ASTM E1097 [11] for all other elements. The radiography testing was conducted in accordance with ASTM E 1032 [16].

The sample extraction and testing procedures are described in full detail in the Final Report [9].

Table 5-1. Naval Surface Warfare Center Carderock Division Testing Plan

<table>
<tr><th>Sample</th><th>Process</th><th>Radiography</th><th>Macro</th><th>Tensile Test</th><th>Micro</th><th>Chemistry</th></tr>
<tr><td>Baseline SMAW E308L-16</td><td rowspan="2">SMAW ½ inch Plate 304L stainless steel</td><td>3</td><td>3</td><td rowspan="2">six transverse tensile samples
(3 @ 2 /plate)</td><td rowspan="4">1 plate if tests 1,2 & 3 good; if problem in any, all 3 plates</td><td rowspan="4">1 if all is well;
all 3 if problems; analyze Cr, Ru, Ni, Cu, Al, Ti</td></tr>
<tr><td>Test SMAW ENiCuRu</td><td>3</td><td>3</td></tr>
<tr><td>Baseline GMAW ER308LSi</td><td rowspan="2">GMAW ¼ inch plate 304L-stailess steel</td><td>3</td><td>3</td><td rowspan="2">6 all weld metal samples
(3@ 2 /plate)</td></tr>
<tr><td>Test GMAW ERNiCuRu</td><td>3</td><td>3</td></tr>
</table>

Al – aluminum

6.0 **Performance Assessment**

6.1 Reduction in Hazardous Air Emissions and Occupational Exposures

Fume studies to assess the hazardous air emissions and occupational exposures generated by the Cr-free ENiCuRu and ERNiCuRu consumables versus those generated by conventional E308L and ER308LSi consumables were conducted during both the laboratory and the field demonstrations in this project.

6.1.1 Laboratory Demonstration Fume Studies

Fume Generation Rate

The results of the FGR study are summarized in Table 6-1. It includes conventional E308L-16 and ERNiCuRu G-IV consumables (as references) that were tested outside this project [17]. The ERNiCuRu G-IV was developed as the last generation of Cr-free SMAW consumable in a preceding SERDP project. Its coating has been optimized in the current Environmental Security Technology Certification Program (ESTCP) project to improve its welding operability. Both ERNiCuRu G-IV and the optimized ERNiCuRu have the same composition electrode rods, but the latter has an optimized coating.

Table 6-1. Fume Generation Rates in Cr-Free and Conventional Consumables

Process	GMAW		SMAW		
Consumable	ERNiCuRu	E308LSi	ENiCuRu	ENiCuRu G-IV	E308L-16
FGR, g/min	0.085	0.089	0.355	0.580	0.198

The two GMAW consumables have equal FGR, which is very low. The significantly higher FGR in the SMAW process is related to decomposition/vaporization of the coating flux in the welding arc. The Cr-free ENiCuRu electrode had 44% higher FGR than the conventional E308L-16 electrode and met the performance objective stated in Table 3-1. The coating optimization of ERNiCuRu conducted during the laboratory demonstration of this project resulted in 39% reduction in the FGR as compared to the ERNiCuRu G-IV (Table 6-1). The FGR characterizes the intensity of particulate emission during welding and does not directly reflect the emission of Cr(VI) in the welding fume.

Cr(VI) Content in Welding Fume

The results of the study on Cr(VI) content in the welding fume of the Cr-free and conventional stainless steel consumables are summarized in Table 6-2. The ENiCuRu consumable provided 98.6% (factor of 71) reduction of the Cr(VI) content in the welding fume as compared with the conventional E308L-16 SMAW electrode and met the performance objective stated in Table 3-1. The extremely low amount of Cr(VI) found in the fume of the Cr-free ENiCuRu consumable is generated by vaporization from the molten welding pool that is diluted with type 304L stainless steel. The optimized coating of the ENiCuRu provided less Cr(VI) in the welding fume as compared to its older version (ENiCuRu G-IV).

Not enough fumes were collected from the ER308LSi or ERNiCuRu GMAW electrodes to determine the Cr(VI) concentration in their fume. Since the valence state of chromium is dependent on what elements are present in the welding consumable, solid electrode wires do not generate a significant amount of Cr(VI). Due to the lack of alkaline elements in the welding consumable, they mostly generate trivalent chromium.

Table 6-2. Cr (VI) Content in Welding Fume of Cr-Free and Conventional Consumables

Process	GMAW		SMAW		
Consumable	**ERNiCuRu**	**E308LSi**	**ENiCuRu**	**ENiCuRu G-IV**	**E308L-16**
Cr (VI), wt.%	**N/A**	**N/A**	**0.037**	**0.097**	**2.62**
% Reduction (Cr-free vs. conventional)	N/A		98.6%	96.3%	N/A

Ruthenium Content in the Welding Fume

The Ru content found using ICP spectrometry in two samples of ENiCuRu welding fume is compared in Table 6-3 with the Ni content and the total Cr content in the fume. The Ru content in the welding fume is extremely low (0.003 wt %), more than one order of magnitude lower than the Cr(VI) content in the fume as shown in Table 6-2.

Table 6-3. Content of Ru, Ni, and Total Cr in Welding Fume of ENiCuRu

Sample	Ni		Total Cr		Ru	
	ppm	wt.%	ppm	wt.%	ppm	wt.%
1	46557	4.7%	1010	0.10%	29	0.003%
2	45236	4.5%	1073	0.11%	27	0.003%

X-Ray Diffraction Study on Welding Fume

The results from the XRD study in the fume of the tested electrodes are summarized in Table 6-4. The XRD spectra are presented in the Final Report [9]. The fume of the ENiCuRu electrode indicates the presence of Ni oxide and Ni-Cu oxide, while the ERNiCuRu fume contained Ni-Cu oxide and Ni-Ti oxide. The presence of the latter can be related to the higher Ti content, which was introduced into the electrode of this consumable to improve the weld metal deoxidation. Both stainless steel consumables contained magnetite compounds, with ER308LSi also containing Ni manganese oxide. The alkali components in the coating of the SMAW E308L-16 consumable resulted in the formation of sodium fluoride (NaF) and potassium chromate (K_2CrO_4). It was shown that Cr(VI) in welding fume of SMAW electrodes is present in alkali oxides as K_2CrO_4 and sodium chromate [18]. No Cr(VI) containing compounds were found in the fume of ENiCuRu.

Table 6-4. Compounds Present in Welding Fume of Cr-Free and Conventional Consumables

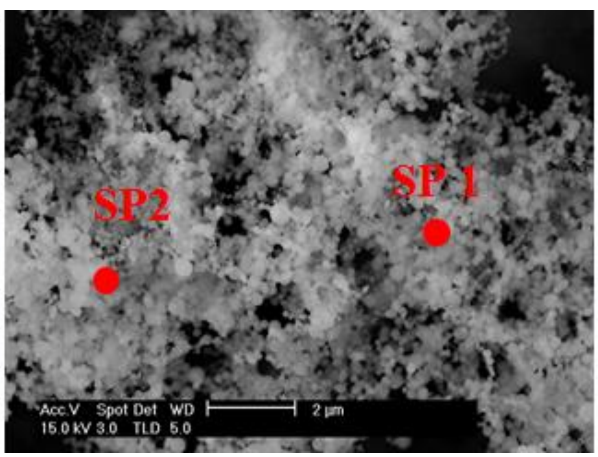
Process	GMAW		SMAW	
Consumable	ERNiCuRu	ER308LSi	ENiCuRu	E308-16
Compounds	$Ni_{.95}Cu_{.05}O$, $Ni_{2.44}Ti_{.77}O_4$	Fe_3O_4, $NiMn_2O_4$	NiO, $Ni_{.90}Cu_{.10}O$	Fe_3O_4, $K_2(Fe,Mn,Cr)O_4$, NaF

Fe – iron, O – oxygen

SEM Analyses on Welding Fume

An example of an UHR SEM image of fume particles collected on stage 8 in the ELPI from welding fume of the ENiCuRu consumable is shown in Figure 6-1. The composition of the tested species reflects the chemical composition of the corresponding welding filler wires: higher Cr and iron (Fe) content in ER308LSi and higher Ni and Cu content in ERNiCuRu. The fume of ENiCuRu contains mostly sodium (Na) and potassium (K) from the coating and Ti, Ni, and Cu from the electrode core wire. The strontium (Sr) present in SP2 on Figure 6-1 comes from the Sr carbonate present in the flux mixture. XEDS spectrum from ENiCuRu fume is shown in Figure 6-2. It indicates alloying elements originating from the core wire (Ni, Ti, Al, Ru), from the electrode coating (Na, magnesium, Sr, K), and from the base metal that vaporized from the welding pool (Fe and Cr).

Elem, wt%	SP1
Na-K[1]	41.0
Mg[2]-K[1]	1.5
Si[3]-K[1]	1.0
K-K[1]	19.7
Ti-K[1]	5.5
Cr-K[1]	1.6
Fe-K[1]	3.1
Ni-K[1]	16.9
Cu-K[1]	9.7
Total	100



Elem, wt%	SP2
Na-K[1]	45.3
Mg[2]- K[1]	1.2
Si[3]-K[1]	0.7
Sr-L[1]	1.4
K-K[1]	16.1
Ti-K[1]	5.5
Fe-K[1]	0.4
Ni-K[1]	19.1
Cu-K[1]	10.3
Total	100

Figure 6-1. UHR SEM Images and XEDS of ENiCuRu Fume Particles Collected on Stage 8

Footnotes specific to this table:

[1] The letters K and L after the element denotes the electronic shell detected by the EDS analyzer.

[2] Mg: magnesium

[3] Si: silicone

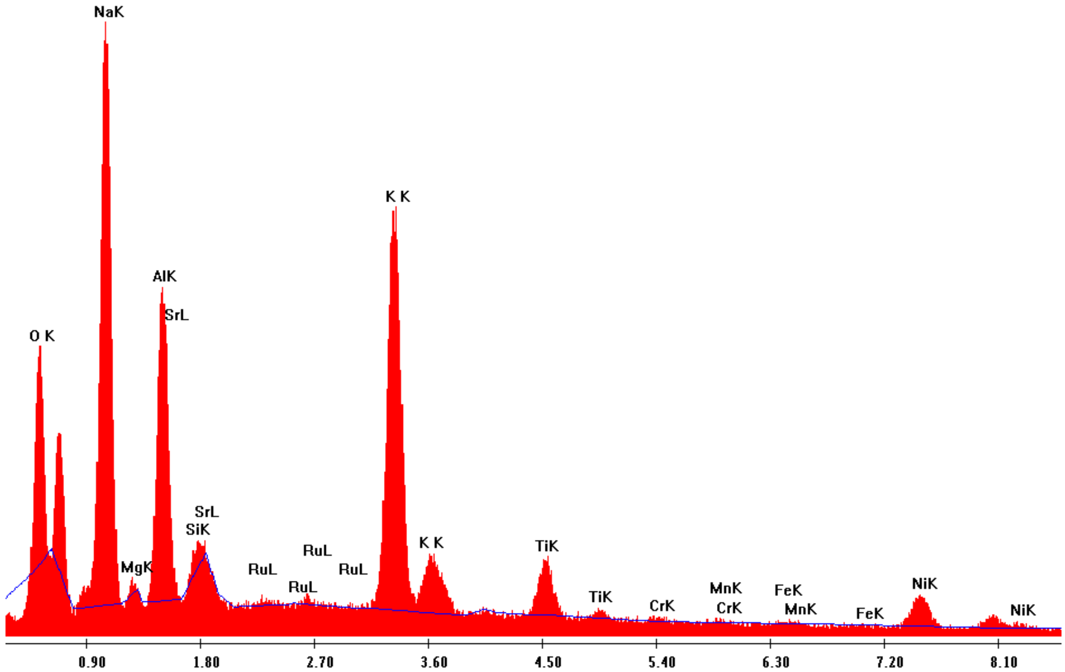


Figure 6-2. XEDS Spectrum from ENiCuRu Fume Collected on Stage 8. Sr and Ru were Detected

6.1.2 Field Demonstration Fume Studies

Cr(VI) Content in Welding Fume of Shielded Metal Arc Electrodes

All data of the Cr(VI) analyses in welding fume generated by the E308L-16 baseline electrode and by the ENiCuRu test electrode and collected using the ELPI, the AS, and the near and far location IH pumps are provided in the Final Report [9]. A summary of the test results is presented in Table 6-5 and in Figures 6-3 through 6-5.

Table 6-5. Cr (VI) Content in Welding Fume of ENiCuRu and E308L-16 Electrodes in $\mu g/m^3$

Collection	ELPI		AS		IH near field		IH far field	
Sample No.	E308L-16	ENiCuRu	E308L-16	ENiCuRu	E308L-16	ENiCuRu	E308L-16	ENiCuRu
1	9.21*	0.801	28.00	0.073	3.920	0.055	1.930	0.0514
2	7.88	0.135	8.96	0.270	2.690	0.197	1.220	0.1510
3	7.92	0.839	24.30	0.240	8.490	0.163	2.090	BDL**
4	15.60	0.209	19.70	0.066				
5	33.60	0.542	8.50	0.170				
6	9.54	0.520						
7	9.10	0.384						
8	11.30	0.150						
9		0.059						
Max	**33.60**	**0.839**	**28.00**	**0.270**	**8.49**	**0.197**	**2.09**	**0.1510**
Min	**7.88**	**0.059**	**8.50**	**0.066**	**2.69**	**0.055**	**1.22**	**0.0514**
Average	**13.02**	**0.4043**	**17.892**	**0.164**	**5.033**	**0.138**	**1.747**	**0.1012**
St. dev.	**8.6815**	**0.2902**	**8.867**	**0.093**	**3.056**	**0.074**	**0.463**	**0.0704**
*Fume collection day:		one	two	three		**BDL: below detection limit		

There are significant sample-to-sample variations in the Cr(VI) content of welding fume collected with the same equipment for each electrode. Significant also are the variations between fume samples of each electrode collected when using different equipment (ELPI, AS, and IH). No obvious relation between these variations and the sequence of testing (test day) was found. Possible sources of variations could be in the fume collection and fume analysis procedures.

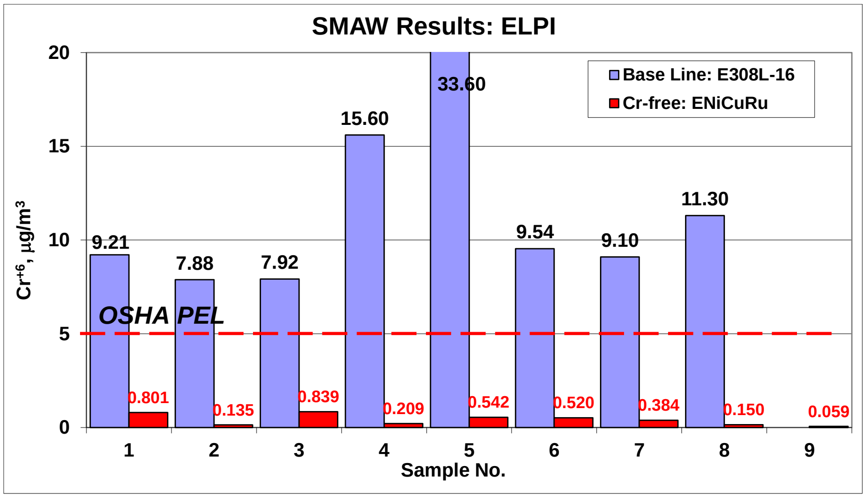


Figure 6-3. Cr(VI) Concentration in the Welding Fume of E308L-16 and ENiCuRu Collected Using ELPI

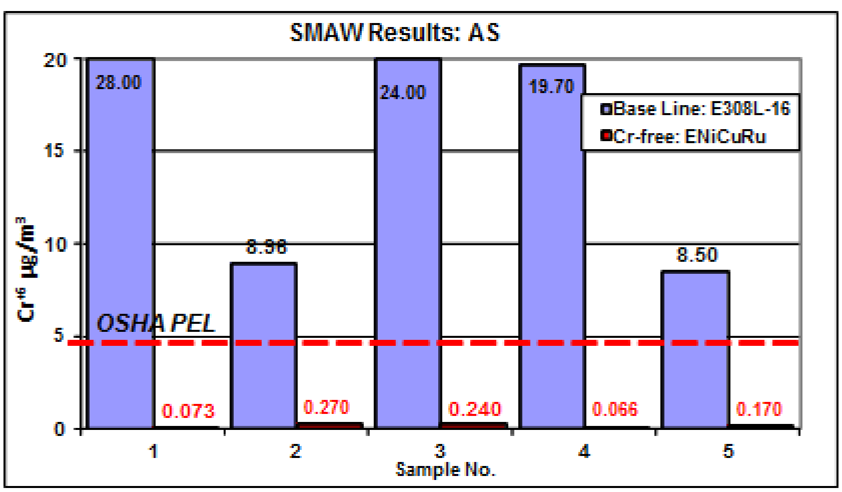


Figure 6-4. Cr(VI) Concentration in the Welding Fume of E308L-16 and ENiCuRu Collected Using AS

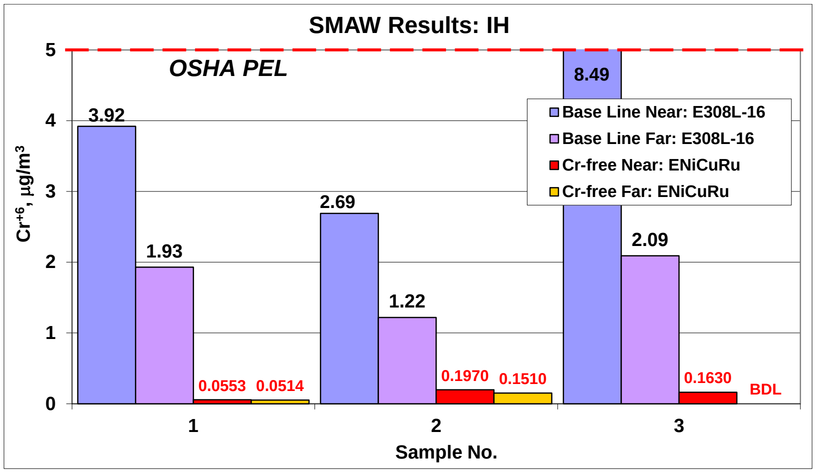


Figure 6-5. Cr(VI) Concentration in the Welding Fume of E308L-16 and ENiCuRu Collected Using IH Pumps at Near and Far Locations from the Welding Arc

In spite of the result variations, the test results allow performance evaluation of the Cr-free ENiCuRu electrode in terms of reduction of Cr(VI) emission compared to the OSHA PEL of 5 $\mu g/m^3$ and to the baseline E308L-16 electrode (Table 6-6).

Table 6-6. Reduction in Percent of Cr(VI) Content in the Welding Fume of ENiCuRu versus the OSHA PEL and E308L-16 Electrode

Collection	ELPI		AS		IH near field		IH far field	
Comparison	vs. OSHA PEL	vs. E308L-16	vs. OSHA PEL	vs. E308L-16	vs. OSHA PEL	vs. E308L-16	vs. OSHA PEL	vs. E308L-16
Max, %	98.82	99.82	98.68	99.76	98.89	99.35	98.97	97.54
Min, %	83.22	89.35	94.60	96.82	96.06	92.68	96.98	87.62
Average, %	91.91	96.89	96.72	98.95	97.23	97.58	97.98	94.21

In summary, out of 20 fume samples generated by the ENiCuRu electrode, 18 samples exceeded the performance objective of 90% exposure reduction compared to OSHA PEL and 19 samples exceeded this objective compared to the E308L electrode. Two ELPI collected samples and one far-field IH sample were close below the 90% objective. Based on the analysis of the test results, it can be concluded that the Cr-free ENiCuRu electrode met the performance objective of reduction in Cr(VI) exposure compared to the OSHA PEL and the conventional type E308L electrode.

Cr(VI) Content in Welding Fume of Gas Metal Arc Electrodes

All results of Cr(VI) analyses in welding fume generated by the ER308LSi baseline electrode and the Cr-free ERNiCuRu electrode collected using the ELPI, the AS, and the IH near and far location pumps are presented in the Final Report [9]. The Cr(VI) content in most of the ER308LSi and ERNiCuRu fume samples collected using IH pumps at near and far field was below the limit of detection or very close above it. For this reason, IH collected samples are not included in the analyses of test results. The concentration of Cr(VI) in the fume collected using ELPI and AS is summarized in Tables 6-7 and 6-8 and Figure 6-6.

Table 6-7. Cr(VI) Content in Welding Fume of ERNiCuRu and ER308LSi Electrodes in $\mu g/m^3$

Collection	ELPI		AS	
Sample No.	ER308LSi	ERNiCuRu	ER308LSi	ERNiCuRu
1	2.470	0.088	0.98	0.118
2	1.330	0.723	1.60	0.654
3	0.738	0.733	1.30	
4	0.572		1.60	
5	0.961			
Max	**2.470**	**0.733**	**1.60**	**0.654**
Min	**0.572**	**0.088**	**0.98**	**0.118**
Average	**1.2142**	**0.51467**	**1.37**	**0.386**
St. deviation	**0.757**	**0.370**	**0.296**	**0.379**

*Fume collection day:	one	two	three	four	five

Table 6-8. Reduction in Percent of Cr(VI) Content in the Welding Fume of ERNiCuRu versus the OSHA PEL and versus ER308LSi

Collection	ELPI		AS	
Comparison	vs. OSHA PEL	vs. ER308LSi	vs. OSHA PEL	vs. ER308LSi
Max, %	98.24	96.44	97.64	92.62
Min, %	85.34	-26.40	86.92	33.27
Average, %	89.71	57.61	92.28	71.28

Compared to the OSHA PEL and the baseline ER308LSi electrode, the ERNiCuRu electrode provided reduction of the exposure to Cr(VI) content correspondingly between 85.3 and 98.2% and up to 96.4%. Most of the Cr(VI) concentrations in the fume of ERNiCuRu and ER308LSi electrodes were below the detection limit of Cr(VI) or closely above it. However, based on the results, it can be concluded that the Cr-free ERNiCuRu electrode met the performance objectives of Cr(VI) exposure reduction stated in Table 3-1. It should be noted that the negative number in Table 6-8 indicates that the maximum Cr(VI) concentration in the welding fume of ERNiCuRu was greater than the minimum Cr(VI) concentration in the welding fume of ER308LSi.

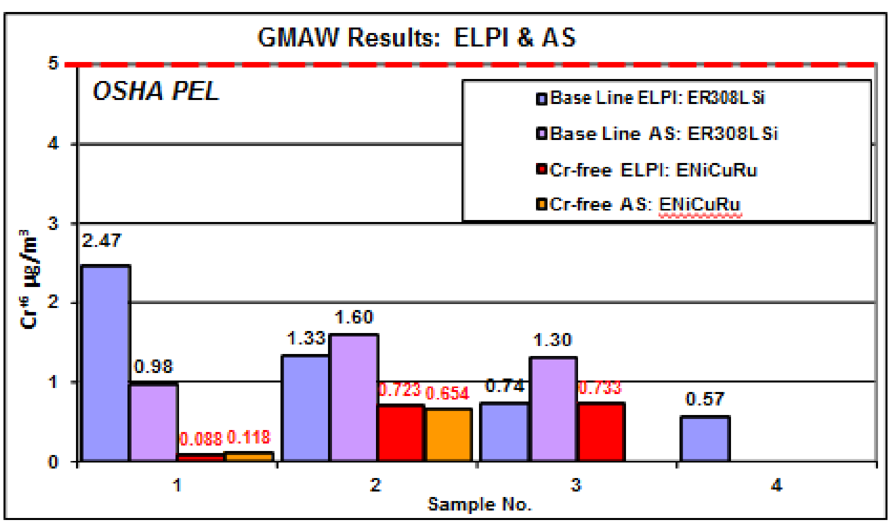


Figure 6-6. Cr(VI) Concentration in the Welding Fume of ER308LSi and ERNiCuRu Collected Using ELPI and AS

Metals Content in Welding Fume of Shielded Metal Arc and Gas Metal Arc Electrodes

The maximum values of metals content in the welding fume of conventional E308L-16 and ER308LSi and Cr-free ENiCuRu and ERNiCuRu consumables are summarized in Tables 6-9 and 6-10. All data of these analyses are presented in the Final Report [9].

Table 6-9. Metals Content in the Welding Fume of SMAW Electrodes (mg/m^3)

Element, mg/m^3	IH-M N		IH-M F		AS		OSHA PEL, mg/m^3
	E308L-16	ENiCuRu	E308L-16	ENiCuRu	E308L-16	ENiCuRu	
Cr	0.01416	0.00255	0.00866	0.00135	0.02068	0.00186	1
Cu	0.0011	0.0068	0.00029	0.00253	0.00207	0.00464	0.1
Fe	0.03357	0.01383	0.00833	0.00481	0.03994	<0.0087	10
Mn	0.02337	0.00099	0.00855	0.00075	0.03595	<0.0017	5
Ni	0.0123833	0.0382333	0.0006687	0.0100633	0.00503	0.0114	1
Ru	<0.0004	<0.0004	<0.0003	<0.0003	<0.0018	<0.0017	N.A.

The content of all main alloy elements in the fume of both SMAW electrodes was between two and three orders of magnitude below the corresponding OSHA PEL (Table 6-9). The Ru content was fairly similar in the fume of both electrodes and most of the measurements were below the limit of quantitation (total measured quantity in the fume <0.2 micrograms μg). There is currently no OSHA PEL for Ru. However, the results correlate well with the Ru content in the welding fume of ENiCuRu (0.003 wt %) measured during the laboratory testing (see Section 6.1.1).

For both SMAW electrodes, the content of the impurity elements arsenic (As), cadmium (Cd), cobalt (Co), molybdenum (Mo), lead (Pb), Ru, vanadium (V), and zinc (Zn) was below the limit of quantitation (<0.2 μg) for most of the measurements. The Sr concentration in the fume of ENiCuRu was very low (between 0.002 and 0.02 milligrams per cubic meter). The Sr in the welding fume originates from the presence of 19 wt % Sr carbonate in the coating of this electrode. There is currently no OSHA PEL for Sr.

Table 6-10. Metals Content in the Welding Fume of GMAW Electrodes (mg/m^3)

Element, mg/m^3	IH-M N		IH-M F		AS		ELPI		OSHA PEL, mg/m^3
	ER308LSi	ERNiCuRu	ER308LSi	ERNiCuRu	ER308LSi	ERNiCuRu	ER308LSi	ERNiCuRu	
Cr	0.00450	0.01529	0.00226	0.00145	0.04198	0.0315	0.1315	0.0195	1
Cu	0.00188	**0.15**		0.00532	0.00452	**0.500**	0.0054	**0.33517**	0.1
Fe	0.04571	0.10503	0.00842	0.00860	0.17768	0.0589	0.2293	0.05939	10
Mn	0.00694	0.00484	0.00418		0.13210	0.0067	0.5604	0.00687	5
Ni	0.00351	0.23310	0.00081	0.07665	0.02287	**1.32**	0.1598	0.97131	1
Ru	<0.0008	0.00266	<0.0005	<0.0008	<0.0083	0.0044	<0.0003	0.0024	N.A.

The content of metal Cr, Fe, and Mn in the fume of both GMAW electrodes was between one and three orders of magnitude below the corresponding OSHA PEL (Table 6.10). The Ni content in the ERNiCuRu exceeded the OSHA PEL in the AS measurement. The Cu content in the fume of ERNiCuRu exceeded the OSHA PEL in three of the measurement methods. Such behavior is expected since ERNiCuRu is a Ni-based welding consumable with a high alloy content of Cu. Similar behavior would be expected in GMAW with other Ni-based consumables. The source of

Ni and Cu in the welding fume is vaporization of molten metal in the welding arc. A possible solution to reduce Ni and Cu in the welding fume of ERNiCuRu is to reduce the arc power by using a low heat input welding process such as cold metal transfer.

The Ru content was fairly similar in the fume of both electrodes and most of the measurements were below the limit of quantitation (total measured quantity in the fume <0.2 μg). The content of the impurity elements As, Cd, Co, Mo, Pb, Ru, Sr, V, and Zn was below the limit of quantitation (<0.2 μg) for most of the measurements. The Sr concentration in the fume of both electrodes was fairly similar and very low.

The results from this study show that the Cr-free ENiCuRu and ERNiCuRu consumables met the objectives to reduce the hazardous air emissions and occupational exposure stated in Table 3.1, except for separate measurements of the Cu and Ni content in the fume of ERNiCuRu.

6.1.3 Field Demonstration Health and Safety Monitoring

The results of collective field screening for α, β, and γ radiation performed using the RD in conjunction with the GECRM, and the ABS measurements of the amount of radiation each person received daily while in the room during welding are summarized in the Final Report [9].

The peak counts of α, β, and γ radiation measured at the welding table, welding rod, welding plates, and on the personnel working in the welding room were in the range of the background peak counts.

The amount of α and β radiation received by the personnel was in the range of the background measurements and the DAC never exceeded the project action levels for Ru isotopes. The concentration of radiation received by the welder was about one order of magnitude below the project action limit, and the DAC hour exposure was zero. These results show that the minor amounts of Ru and Sr found in the welding fume of the Cr-free ENiCuRu and ERNiCuRu electrodes cannot result in overexposure to radiation of the welding personnel and that the performance objectives regarding occupational exposure set in Table 3-1 were met.

6.2 Weld Mechanical Properties

6.2.1 Laboratory Demonstration Testing of Weld Mechanical Properties

The results of ENiCuRu all weld metal and of ERNiCuRu cross weld tensile testing are summarized in Tables 6-11 and 6-12.

The yield strength of ENiCuRu exceeded the minimum specified value of type 304L stainless steel by a factor of 2.17. The tensile strength of all weld metal exceeded the minimum values of type 304L steel and of conventional E316L weld metal and was slightly below the minimum value of E308L. The El in the test weld was lower than in the reference materials.

Table 6-11. Tensile Properties of All Weld Metal of Cr-Free ENiCuRu Consumable

Weld	YS, MPa	YS, ksi	UTS, MPa	UTS, ksi	El, %
ENiCuRu	**370**	**53**	**501**	**72**	**25**
304L St. Steel Min. Values	170	24	480	69	40
AWS A5.4-92 Min: E316L	-	-	490	70	30
AWS A5.4-92 Min: E308L	-	-	520	75	35

YS – yield strength, UTS – ultimate tensile strength

Table 6-12. Tensile Properties of Cross Welds of Cr-Free ERNiCuRu Consumable

Weld	YS MPa	YS ksi	UTS MPa	UTS ksi	El %
ERNiCuRu (average of 3)	**327**	**53**	**584**	**83**	**34**
304L St. Steel Min. Values	170	24	480	69	40
AWS A5.4-92 Min: ER316L	-	-	490	70	30
AWS A5.4-92 Min: ER308L	-	-	520	75	30

The yield and tensile strength in cross weld samples of ERNiCuRu exceeded the minimum requirements for type 304L stainless steel and conventional ER308L and ER316L weld metal. The 34% El found in cross weld tensile testing of ERNiCuRu can be considered as proof of overall good joint ductility, due to non-uniform strain distribution in tensile testing of cross weld samples.

No cracks were found in any of the three ENiCuRu side bent samples or in the three ERNiCuRu face bend samples. Thus, the performance objectives stated in Table 3-1 were met for both Cr-free consumables except for the El in all weld metal of ENiCuRu electrode.

6.2.2 Field Demonstration Testing of Weld Mechanical Properties

The tensile testing results of the all weld metal SMAW E308L baseline welds and ENiCuRu test welds are summarized in Table 6-13.

The yield and tensile strength, as well as the El of the baseline E308L welds exceeded the minimum requirement for Type 304L steel based metal and for E316L and E308L weld metal. The yield and tensile strength of all test ENiCuRu welds exceeded the minimum requirement for type 304L steel based metal. The tensile strength of two of these welds and the El in one of them exceeded the minimum requirements for E316L and E308L welds. The lower tensile strength and El values in test weld T004 (Table 6-13) can be related to the high level of defects found in this weld. Weld T004 failed the radiography test as shown in Table 6-15.

The tensile testing results of transverse samples of the baseline ER308LSi and the test ERNiCuRu welds are summarized in Table 6-14. All test samples of the baseline ER308LSi welds exceeded the minimum yield strength of type 304L steel but failed to meet the minimum for tensile strength and El requirements. All of these welds had brittle failure in the weld metal. The poor mechanical properties can be related to the continuous lack of fusion welding in these welds.

Table 6-13. Tensile Testing Results for All Weld Metal Samples of E308L and ENiCuRu Welds

Process / Electrode	Weld I.D.	NSWCCD I.D.	Specimen I.D.	YS, ksi	UTS, ksi	El, %	Reduction in Area, %
SMAW E308L-16	B003	F531	T1	64.5	89.5	43	60
			T2	61	85.5	42	63
	B004	F532	T1	66	88.5	44	60
			T2	65	88.5	43	59
	B005	F533	T1	64	89.5	44	66
			T2	64	88.5	45	63
			Average	64.1	88.3	43.5	61.8
SMAW ENiCuRu	T003	F534	T1	43.5	68.5	22	35
			T2	49.5	77	27	29
	T004	F535	T1	45.4	60.5	14	20
			T2	44.1	61.5	15	24
	T005	F536	T1	49.3	79	39	46
			T2	45.2	69	21	33
			Average	46.2	69.3	23.0	31.2
304L St. Steel Min. Values				24	69	40	-
AWS A5.4-92 Min: E316L				-	70	30	-
AWS A5.4-92 Min: E308L				-	75	35	-
Threshold Min. Limit		Exceed			Failed		

Table 6-14. Tensile Testing Results for Transverse Weld Samples of ER308LSi and ERNiCuRu Welds

Process / Electrode	Weld I.D.	NSWCCD I.D.	Specimen I.D.	YS, ksi	UTS, ksi	El, %	Failure Location	Fracture Mode
GMAW ER308LSi	B01E1	F527	T1	46.3	56	3.1	Weld	Brittle
			T2	45.5	52	2.1	Weld	Brittle
	B002	F525	T1	42.9	47.1	4.3	Weld	Brittle
			T2	46.8	53.5	3.6	Weld	Brittle
	B0E3	F526	T1	43.1	50	3.2	Weld	Brittle
			T2	44.7	47.4	4.1	Weld	Brittle
	Average			44.9	51	3.4	-	-
GMAW ERNiCuRu	T008G	F537	T1	46.9	78.5	22	Weld	Ductile
			T2	46	80	22	Weld	Ductile
	T009G	F538	T1	44.9	79	22	Weld	Ductile
			T2	45.9	80.5	25	Weld	Ductile
	T0010G	F539	T1	47.2	80	21	Weld	Ductile
			T2	44.4	77.5	19	Weld	Ductile
			Average	45.9	79.3	21.8	-	-
304L St. Steel Min. Values				24	69	40	-	-
AWS A5.4-92 Min: ER316L				-	70	30	-	-
AWS A5.4-92 Min: ER308L				-	75	30	-	-
Threshold Min. Limit			Exceed			Failed		

All ERNiCuRu test welds exceeded the minimum strength requirements for type 304L stainless steel and for ER316L and ER308L weld metal. The El results of the cross weld tensile test cannot be used to evaluate the weld metal ductility. However, these results show that the baseline ER208LSi welds had poor ductility compared to the test ERNiCuRu. This can be attributed to the high level of defects found in the test welds of both electrodes. All ER308LSi baseline welds and all ERNiCuRu test welds failed the radiography test (Table 6-16).

The tensile test results prove that the Cr-free ENiCuRu and ERNiCuRu consumables are capable of producing welds that meet and exceed the mechanical properties of type 304L stainless steel and of the conventional welding consumables E316L and E308L.

6.3 Weld Quality Evaluation

6.3.1 Weld Quality Evaluation during Laboratory Demonstration

Radiographic images and micro-sections of weld test assemblies made with the ENiCuRu and ERNiCuRu electrodes and of filled welds made with the ENiCuRu electrode are provided in the Final Report [9]. One small slag inclusion in the ENiCuRu weld and slight undercuts in the ERNiCuRu weld were identified in the radiographic images. No cracks or other types of welding defects and imperfections were found in the test assemblies and filled welds. All welds made during the laboratory demonstrations passed the requirements of ANSI/AWS B2.1-2000 and ANSI/AWS A5.11-97, and met the performance objectives set in Table 3-1.

6.3.2 Weld Quality Evaluation during Field Testing

Radiographic images of the weld test assemblies made with the baseline E308L-16 and ER308LSi electrodes and with the test ENiCuRu and ERNiCuRu electrodes are presented in the Final Report [9]. Test reports for the radiographic results of all test weld assemblies are shown in Tables 6-15 and 6-16. The radiographic films were too blurred for nondestructive evaluation (NDE) Inspector 1 to evaluate the quality of the SMAW test welds (Table 6-15). Inspector 2 concluded that two of the baseline welds and one test weld passed the requirements of ANSI/AWS B2.1-2000 and ANSI/AWS A5.11-97, one test weld failed these requirements due to lack of fusion, and was inconclusive for one baseline weld and one test weld.

Both the ER30LSi welds and the test ERNiCuRu welds failed to meet the requirements of ANSI/AWS B2.1-2000 and ANSI/AWS A5.11-97 due to lack of fusion, porosity, undercuts, and insufficient fill defects (Table 6-16).

The macro- and micro-structure of the test weld assemblies produced with baseline E308L-16 and ER308LSi electrodes and with test ENiCuRu and ERNiCuRu electrodes are presented in the Final Report [9]. The weld metal macro-sections show large side-wall lack of fusion defects in two of the E308-16 baseline welds and in one of the ENiCuRu test welds. An area of possible small size weld metal lack of fusion and slag inclusion defects was found in test weld T004. Such defects could be the reason for the lower tensile properties of this weld as compared to the other two ENiCuRu welds.

Table 6-15. Radiography Test Report on E308L-16 and Test ENiCuRu Weld Assemblies

Electrode / Process	Sample ID	NDE Inspector 1*		NDE Inspector 2**	
		Pass / Fail	Remarks	Pass / Fail	Remarks
SMAW Baseline E308L-16	F531	?	Too blurred	P	Satisfactory
	F532	?	Too blurred	?	Porosity, insufficient fill, possible lack of fusion
	F533	?	Too blurred	P	
SMAW Test ENiCuRu	F534	?	Too blurred	P	Some lack of fusion
	F535	?	Too blurred	F	Lack of fusion
	F536	?	Too blurred	?	Possible lack of fusion, porosity

* H. Nguyen (Level II – NDE Inspector) and R. McConnehey (Level III– NDE Inspector), Point Mugu, CA
** G. Frank, Code 611; Welding, Processing and NDE Branch, NSWC, Carderock Division, Maryland

Table 6-16. Radiography Test Report on ER308LSi and Test ERNiCuRu Weld Assemblies

Electrode / Process	Sample ID	NDE Inspector 1*		NDE Inspector 2**	
		Pass / Fail	Remarks	Pass / Fail	Remarks
GMAW Baseline ER308LSi	F525	F	Lack of fusion	F	Lack of fusion, cracks
	F526	F	Lack of fusion	F	Porosity, lack of fusion
	F527	F	Lack of fusion	F	Porosity, lack of fusion
GMAW Test ERNiCuRu	F537	F	Porosity and undercutting	F	Excessive lack of fusion, insufficient fill, undercut
	F538	F	Lack of fusion, porosity	F	Excessive lack of fusion, insufficient fill, undercut
	F539	F	Porosity and undercutting	F	Excessive lack of fusion, insufficient fill, undercut

* H. Nguyen (Level II – NDE Inspector) and R. McConnehey (Level III– NDE Inspector), Point Mugu, CA
** G. Frank, Code 611; Welding, Processing and NDE Branch, NSWC, Carderock Division, Maryland

All macro-sections of baseline ER308LSi welds showed large root/side-wall lack of fusion defects that formed during the deposition of the second pass. The side-wall lack of fusion defects were oriented almost normal to the applied stress during tensile testing thus reducing the load-bearing weld cross section. The low strength, extremely low ductility, and brittle failure in the ER308LSi welds (Table 6-14) were related to the side-wall lack of fusion defects.

The three macro-sections of ERNiCuRu test welds had root lack of fusion defects. These were oriented parallel to the applied stress during tensile testing and did not reduce the load-bearing weld cross section. However, the lower ductility in the ERNiCuRu test welds (Table 6-14) can be related to the root lack of fusion and the undercut defects found in these welds.

The weld quality evaluation has shown that part of the ENiCuRu test welds met the performance objectives set in Table 3-1, but one ENiCuRu and all of the ERNiCuRu test welds did not meet these performance objectives. The latter can be related to welder's inexperience, since some of the E308L-16 and all of the ER308LSi baseline welds also did not meet these objectives.

6.4 Welding Operability Evaluation

6.4.1 Weld Operability Evaluation during Laboratory Demonstration

The welding operability evaluation of the ENiCuRu consumable generated by the two experienced welders who produced 0.75 inch thick weld test assembly and 0.25 inch thick fillet welds is presented in the Final Report [9]. Based on 15 evaluation criteria and a ranking scheme of 1 to 10, the welding operability of the ENiCuRu electrode in flat position was rated at 9.4 and 9.5. This ranking was comparable to other Ni-based shielded metal arc electrodes and very close to conventional stainless steel shielded metal arc electrodes. The ENiCuRu electrode also performed well in out-of-position (vertical down and overhead) welding. Based on the results from welders' evaluation, it can be concluded that ENiCuRu electrode has acceptable welding operability and met the performance objectives set in Table 3-1.

6.4.2 Weld Operability Evaluation during Field Demonstration

During the field demonstration, the welding operability of the tested electrodes was evaluated by the welder who produced the test welds. The welder's evaluation of the welding operability of these electrodes is provided in the Final Report [9]. The main comments of the welder included difficulties in controlling the weld pool and the weld penetration that were related to the low fluidity of the liquid metal and its low and thermal conductivity. This is a typical behavior of the weld pool in Ni-based filler metals. The welder also commented that specialized training and longer term experience would be needed to achieve a better weld quality with the Cr-free welding consumables.

7.0 Cost Assessment

The total cost assessment associated with replacing type 308 stainless steel filler metal with Cr-free welding consumables includes the following major categories: 1) the cost of the Cr-free filler wire versus the cost of type 308 filler metal; 2) the cost reduction associated with the reduced ventilation requirement (as compared to the new OSHA PEL of 5 $\mu g/m^3$ 8-hour-TWA) when welding with Cr-free welding consumables.

7.1 Cost Differential between Type 308 and Cr-free Welding Consumables

7.1.1 Background

A detailed cost analysis for the substitution of Cr-free welding consumables for standard type 308 filler metals for the welding of stainless steel was developed in 2006 under SERDP Project PP-1415 “Development of Chromium-Free Welding Consumables for Stainless Steels” [3]. Although it is anticipated that the cost of the Ni-Cu-Pd Cr-free filler material will come down when it is produced in larger quantities, an initial cost of $56/lb was estimated in 2006. This compares to an approximate retail cost of the type 308 filler material of $6/lb. To quantify how these different filler metal costs might translate into overall welding costs, 10 specific welding applications were analyzed. The industry sectors from which the applications were selected included shipbuilding, transportation and storage tanks, and general fabrication. The joint designs included V-groove butt welds between pipe and plate, as well as T joints with fillet welds. The list of assumptions used in this analysis is provided in the Final Report [9].

7.1.2 Updated Status of Filler Metal Development and Cost

In 2011, weld testing of the new filler metal, 91% Ni, 8% Cu, and 1% Ru, was conducted at a DoD facility to evaluate weld soundness and establish typical fume production in the field. A simple cost analysis similar to that described in Section 7.1.1 was conducted on this new alloy using updated 2011 commodity pricing. The estimated price per pound for the 91Ni-8Cu-1Ru filler metal is $37/ lb, significantly lower than the Pd containing filler material used for the initial cost assessment. For SMAW electrodes, this lower material cost translates to a cost of approximately $31/lb, and for GMAW electrode wire, about $42/lb. Calculations were conducted on the applications evaluated previously to show the effect on cost when using the 91Ni-8Cu-1Ru filler metal. This updated summary of the results reflecting the significantly lower cost (compared to the Pd containing wire) associated with the Ru addition is shown in Table 7-1.

Table 7-1. Welded Joints Cost ($) Summary

			308 Filler Material		91Ni-8Cu-1Ru Filler Material		
Industry	Joint description	Process	Cost/ft (plate) or cost/joint (plate)	Filler metal cost	Cost/ft (plate) or cost/joint (plate)	Filler metal cost	**% cost increase**
Ship building/pressure vessels	6" dia pipe	SMAW	73.7	7.2	110.3	43.7	**50**
	6" dia pipe	GMAW	24.5	4.4	52.2	33.2	**113**
	12" dia pipe	GMAW	56.2	15.9	162.7	121	**190**
	3/16" fillet weld	GMAW	7.4	0.8	13.6	6.7	**83**
Tanks	3/16" butt weld	GMAW	5.4	0.3	8.4	2.9	**56**
	3/8" butt weld	SMAW	44.1	6.5	78.2	40	**77**
	3/8" butt weld	GMAW	8.8	3.7	35.7	30.2	**306**
General fabrication	3/16" fillet weld	GMAW	2.2	0.8	8.3	6.7	**279**
	1/4" fillet weld	SMAW	5.2	2.7	18.7	16.14	**259**
	1/4" fillet weld	GMAW	4	1.5	15	12.2	**276**

7.1.3 Cost Reduction Associated with Application of Cr-Free Consumables

When OSHA established the new ventilation requirements for reducing exposure to Cr(VI) it stated that the primary methods for reducing such exposure are local exhaust ventilation and improvement of general dilution ventilation. In addition, it is anticipated that, in many cases, a welder will use PPE with a respirator when welding stainless steels. Therefore, this cost assessment is based on the assumption that a typical fabrication facility will incur additional costs for improved general and local ventilation, as well as PPE, as a result of the new OSHA regulation.

There are over 450,000 welders in the United States, and it is estimated that up to 5% of these welders use stainless steel, so it is clear that the issue of Cr(VI) affects a significant number of workers. Numerous general considerations are associated with ventilation decisions regarding the new OSHA ventilation requirements, including issues such as the size of the fabrication facility and whether or not welding is being conducted in a confined space. Every case will be different; this analysis will be based on two typical cases: a relatively large fabrication space and a relatively small fabrication space. It is important to note that this comparison represents very generic cases, and should only be used as a guideline. In addition to the overall size of the facility, many specific factors must be considered that will affect ventilation requirements for each location. Examples of other factors to be considered include location and number of roof and wall ventilators, overhead doors and obstructions, make-up air exchange systems, welding parameters, working hours, annual consumable usage, and type of welding processes used.

For the purposes of this generic comparison, the two different weld shop sizes considered were a 60 ft by 30 ft shop with 12 welders, and a 200 ft x 100 ft shop with 36 welders. Assumptions in each case include: single shift, welding parameters which range between 90 and 150 amps, overhead obstructions (cranes) and no wall ventilators, and a heating, ventilating, and air conditioning system is present as well an air exchange system. In the case of the larger shop, it is assumed there are five roof ventilators (@ 1,000 CFM each), four overhead doors, and the annual consumable usage is estimated at 60,000 lb/year. For the smaller shop, it is assumed there are two roof ventilators (at 1,000 CFM each), two overhead doors, and the annual consumable usage is estimated at 20,000 lb/year. In each case, it is assumed that SMAW, GMAW, and GTAW processes are being used. The extent to which the SMAW process is being used will play a significant role in filter replacement frequency (higher usages of SMAW will require more frequent filter replacements), but there was no attempt to quantify this detail.

Lincoln Electric provided quotes for ventilation systems used for the comparison. The system costs include both a general ventilation system and a source extraction system. The general system is a U-shaped "push-pull" type system. This will provide a continuous positive and negative air flow over the weld area. The source ventilation system includes pivoting and telescopic extraction arms for each welding booth. Other costs considered include the costs of personal protective ventilation suits and air monitoring. Considering all of the aforementioned assumptions and information, the summary below compares typical ventilation system purchase cost differences between a shop that welds stainless steel and therefore is subject to the new OSHA requirements versus a location where ventilation cannot be easily implemented, such as inside a storage tank. These results are summarized Table 7-2.

Table 7-2. Ventilation Systems Cost ($) Summary

Weld Shop Size	Number of Welders	Ventilation System	Initial Purchase Expense	Recurring Expense
200’ x 100’	36	New OSHA Compliant	$700,000	$50,000
		New OSHA Non-compliant	$410,000	$20,000
60’ x 30’	12	New OSHA Compliant	$162,000	$20,000
		New OSHA Non-compliant	$100,000	$10,000

Example of 200 ft x 100 ft Welding Shop – Comparison of Costs

As mentioned, Lincoln Electric provided the ventilation system quotes that were used for this analysis. The total estimated cost for a ventilation system capable of meeting the new OSHA requirement is $660,000. This includes both general and source extraction systems. The ventilation systems include "self-cleaning" capability, but there would be additional costs associated with filter changes and the special High Efficiency Particulate Air (HEPA) filters are much more expensive than conventional filters. Every case will be different, but for the purpose of this generic analysis, an annual filter replacement cost of $25,000 was used. The cost of personal protective ventilation suits for 36 welders is estimated to be $36,000. The cost associated with air monitoring is estimated at $25,000/year. In summary, the initial cost associated with purchasing ventilation equipment to meet the new OSHA standard for a 200 ft x 100 ft welding shop with 36 welders is approximately $700,000. The recurring costs are estimated to be $50,000/year.

In comparison, the total estimated cost for a new OSHA requirement non-compliant ventilation system is $410,000, and the recurring costs are estimated at $20,000/year. To summarize, this analysis indicates the requirements for approximately $300,000 in additional funding to purchase ventilation equipment, and $30,000/year in additional expenses associated with conforming to the new OSHA standard for a welding shop of this size.

Example of 60 ft x 30 ft Welding Shop – Comparison of Costs

The total estimated cost based on the Lincoln quotes for a ventilation system capable of meeting the new OSHA requirement is $150,000. The personal protective suits for 12 welders are estimated to cost $12,000, bringing the total initial equipment cost to $162,000. The recurring costs discussed previously are estimated at $20,000/year for a shop this size.

The estimated cost for a new OSHA requirement non-compliant ventilation system for a shop of this size is $100,000 and the recurring costs are estimated at $10,000/year. In summary, the OSHA ventilation requirement associated with Cr(VI) results is an estimated $50,000 additional capital equipment expense and an additional $10,000 year in recurring expenses.

7.1.4 One Year Cost Analysis Based on Filler Metal Costs

For the purposes of better understanding the financial impact of the OSHA Cr(VI) lower exposure requirement versus the additional cost associated with the Cr-free wire, three welding shop scenarios are compared:

Scenario #1 – 200 ft x 100 ft Welding Shop

Since an assumption was made that 60,000 lb of electrode would be consumed annually in the large sized shop, some simple calculations can be made to develop an understanding of costs over a 10-year period. Using an ER308 filler metal cost of $6/lb will result in a total filler metal cost of $360,000 per year. The Cr-free wire priced at $42/lb will result in a total filler metal cost of $2,520,000 per year. This amount obviously far exceeds the savings that would result from the reduced ventilation requirement.

Scenario #2 - 60 ft x 30 ft Welding Shop

In this case, it is assumed that 20,000 lb of electrode would be consumed annually. Therefore, the filler metal cost would come to $120,000 for the ER308 wire and $840,000 for the Cr-free wire, again far exceeding the ventilation equipment savings that would be realized by using the Cr-free 91Ni-8Cu-1Ru wire.

In summary, this analysis indicates that the current estimated $42/lb cost (for GMAW wire, $31/lb for SMAW wire) of the 91Ni-8Cu-1Ru wire would be financially prohibitive in most cases, even considering the significant savings possible with the reduced ventilation requirement.

Scenario #3 – 60 ft x 30 ft Welding Shop in which only 10% of the Welding is Stainless Steel

In this more realistic scenario, it is assumed that 90% of the welding in the shop is on metals other than stainless steel. In such a case, the ventilation requirements would not necessarily change, but the impact of the cost of the stainless steel filler material would be much less. The filler metal cost (assuming 2,000 lb of electrode is consumed annually) comparison that can be used is $12,000 for the ER308 wire and $84,000 for the Cr-free wire for a difference of $72,000.

This compares to the $62,000 additional purchase expense associated with the special ventilation equipment and the additional $10,000 of recurring costs. It should also be pointed that there will be additional expenses associated with the depreciation of the more expensive special ventilation equipment. In summary, this scenario illustrates that shops that weld only a very small amount of stainless steel could potentially realize a cost reduction by switching to the Cr-free filler material.

7.2 Stainless Steel Welding in Locations with Limited Access to Ventilation

The assessments of Section 7.1 focused on the "trade-off" in costs associated with the additional cost of the Cr-free filler material versus the additional cost of ventilation required by OSHA when standard stainless steel filler materials are used. However, another very important consideration to the Navy that should be addressed is the possibility that there are many locations (boiler rooms, etc.) on Navy vessels where welding and/or welding repair work is conducted which don't offer the possibility to properly and/or easily ventilate. In these cases, self-contained PPE could be used for the welders, but this still does not address the elimination of the Cr(VI) present in the welding fumes that would accumulate (and remain) in the area after the welding is completed. In such cases, it is possible that OSHA regulations will not allow welding to be conducted, and therefore, Cr-free filler materials may be the only solution.

8.0 Implementation Issues

One possible issue related to the implementation of the Cr-free ENiCuRu and ERNiCuRu welding consumables may be the absence of OSHA PEL for Ru in welding fume. This issue can be addressed by conducting related studies at the Toxicology Department of Navy and Marine Corps Public Health Center Comprehensive Industrial Hygiene Laboratory and/or at the Health Effects Laboratory Division of NIOSH. It is recommended that a PEL for Ru be explored at the Naval Medical Research Unit, Dayton, Ohio.

Another possible implementation issue for the Cr-free welding consumables could be the need of providing additional training to welders who have no experience working with Ni-based welding consumables.

Finally, only about 3% of welding conducted at DoD facilities is stainless steel welding. However, those efforts are performed at highly specialized facilities such as TEAD where strict emission and occupational safety and health controls are enforced. Meeting the OSHA requirements for Cr(VI) emissions by using ventilation systems in such facilities may not always be possible or economically feasible. For example, repair work on Navy vessels in locations where installation of ventilation systems is impossible (i.e., boiler rooms) would require using Cr-free welding consumables. As shown in Section 7, in production and repair facilities that perform a comparatively small fraction of stainless steel welding, the usage of Cr-free consumables can be more economical compared to installation and maintenance of specialized ventilation systems for Cr(VI) mitigation.

9.0 **References**

1. OSHA Standards and Regulations (Standards - 29 CFR) Chromium (VI) - 1910.1026.

2. OSHA Standards and Regulations, Occupational Exposure to Hexavalent Chromium.

3. SERDP Project PP-1415 “Development of Chromium-Free Welding Consumables for Stainless Steels”, Final Report, The Ohio State University, January 2009.

4. ANSI/ AWS D1.6/D1.6M:2007, Structural Welding Code – Stainless Steel.

5. ANSI/AWS A5.11-97, Specification for Nickel and Nickel-Alloy Welding Electrodes for Shielded Metal Arc Welding.

6. ANSI/AWS B4.0-98, Standard Methods for Mechanical Testing of Welds.

7. ANSI/AWS A5.4-92, Specification for Stainless Steel Electrodes for Shielded Metal Arc Welding.

8. ASTM E8, Standard Methods of Tension Testing of Metallic Materials.

9. ESTCP Project WP-200903 “Introduction and Validation of Cr-free Consumables for Welding Stainless Steels”, Final Report, The Ohio State University, January 2014.

10. ASTM E142, Standard Method for Controlling Quality of Radiographic Testing.

11. ASTM E1097-07/CTP 3005/DCP, Standard Guide for Determination of Various Elements by Direct Current Plasma Atomic Emission Spectrometry.

12. ASTM E1621-09/CTP 3093/XRF, Standard Guide for X-Ray Emission Spectrometric Analysis.

13. ASTM E1019-08/CTP 3097/IG, Standard Test Methods for Determination of Carbon, Sulfur, Nitrogen, and Oxygen in Steel, Iron, Nickel, and Cobalt Alloys be Various Combinations of Fusion Techniques.

14. ANSI/AWS F1.2-2006, Laboratory Method for Measuring Fume Generation Rates and Total Fume Emission of Welding and Allied Processes.

15. ASTM 407, Standard Practice for Microetching Metals and Alloys.

16. Standard Test Method for Radiographic Examination of Weldments.

17. Sowards J.W., D. Liang, B.T. Alexandrov, G.S Frankel, J.C. Lippold. 2011. A New Chromium-free Welding Consumable for Joining Austenitic Stainless Steels, Welding Journal, 90, pp. 63s – 76s.

18. Kimura, S., Kobayashi, M., Godai, T., and Minato, S. 1979. Investigations on Chromium in Stainless Steel Welding Fumes. Welding Journal, 58, pp. 195s - 204s.

10.0 **Points of Contact**

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Kathleen Paulson/ Tom Torres	NAVFAC EXWC 1100 23rd Street Port Hueneme, Ca 93043	805-982-4984 805-982-4832 Kathleen.paulson@navy.mil Tom.Torres@navy.mil	Project Manager
Dr. Boian T. Alexandrov	Ohio State University Welding Engineering Program, Dept. of Materials Science and Engineering 1248 Arthur E. Adams Drive Columbus, OH 43221	614-292-1735, 614-292-6842 Alexandrov.1@osu.edu http://weldingengineering.osu.edu/materials/	Principal Investigator (PI)/Technical Lead for Cr–free Consumables
Dr. John Lippold	Ohio State University, Room 136 Welding Engineering Program, Dept. of Materials Science and Engineering 1248 Arthur E. Adams Drive, Columbus, OH 43221	614-292-2466 lippold.1@osu.edu	PI Supervisor for Cr-free Consumables
Gene Franke	NSWCCD Welding, Processing, & NDE Branch, Code 611 9500 MacArthur Blvd. West Bethesda, MD 20817-5700	301-227-5571 301-227-5576 Gene.Franke@navy.mil	Welding Engineer & Weld Quality Test Manager
Brent Hunt	General Engineer Ammunition, Equipment Division 1Tooele Army Depot Tooele, UT 84074	790-5045 435-833-5045 brent.hunt1@us.army.mil	Local coordinator for TEAD AED
Tiffany Looff	Environmental Cost Management 3525 Hyland Ave, Suite 200 Costa Mesa, CA 92626-44469	480-358-1480 480-358-1475 tlooff@ecostmanage.com	Field Team Lead for Contract Laboratory for OSH&E Samples
Dr. K. James Hay	ERDC/CERL, Environmental Processes Branch P.O. Box 9005, Champaign, IL 61826-9005	217-373-3485 217-373-3430 kent.j.hay@usace.army.mil	Army Liaison & Project QA/QC

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Michael L. Hanson	USCG Aviation Logistics Center USCG, Safety, Bldg. 79, Weeksville Hwy, Elizabeth City, NC 27909	252-312-9084 252-335-6875 Michael.L.Hanson@uscg.mil	USCG Liaison & Project QA/QC
Dr. Chang-Yu Wu	University of Florida, Dept of Environmental Engineering Sciences, Gainesville, FL 32611-6450	352-392-0845 352-392-3076, cywu@ufl.edu, http://www.ees.ufl.edu/homepp/cywu	PI for TMS part of Demo
Dr. Charles A. Kubrock	Chemistry Team Leader, Health Surveillance Lab Navy Envi & Prev. Med. Unit # 5 3235 Albacore Alley, Naval Station San Diego, CA 92136-5199	619-556-1427 619-556-1497 charles.kubrock@med.navy.mil	Laboratory Analysis & OSH Testing Advisor